Fire-LCA Guidelines

NICe project 04053
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Abstract

Fire-LCA is an LCA method that incorporates fires as one possible end of life scenario. It was developed by SP and IVL in order to be able to assess lifecycle aspects of the fire performance of products. This report gives guidelines on how to perform a Fire-LCA study. They are written based on the experience made during the development and application of the Fire-LCA methodology to different case studies. An application of the method as defined within the Guidelines has been made by a research group unfamiliar with the previous applications of the model. This superficial application is presented to illustrate that the guidelines are written in a logical and comprehensive manner and can be used as a starting point for people experienced in fire and LCA analysis to conduct a Fire-LCA analysis.

Key words: Guidelines, Fire-LCA
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Sammanfattning

Rapporten ger guidelines för hur man ska göra en Fire-LCA analys. Råden som ges är baserade på de erfarenheter SP och IVL har gjort under utvecklandet av Fire-LCA metoden samt dess användning på ett par fall studier.

Preface

These Guidelines are developed based on experience from the development and application of the Fire-LCA model to different case studies by SP and IVL. Apart from the authors, several people have contributed to the development of the model and also put a lot of effort into the case studies. These include Per Blomqvist, Antal Boldizar, Kenneth Möller and Lars Rosell at SP who are all thanked for their contribution throughout the Fire-LCA work.

The Guidelines in this report were tested by VTT by using the guidelines in order to conduct a small test study. Several people took active part in this including Jukka Hietaniemi, Timo Korhonen, Esko Mikkola, Tuuli Oksanen, Sirje Vares and Henry Weckman who are all thanked for their help.

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## List of abbreviations

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<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>BaP</td>
<td>benzo(a)pyrene</td>
</tr>
<tr>
<td>CFBC</td>
<td>Circulating Fluidized-Bed Combustor</td>
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<tr>
<td>E&amp;E</td>
<td>Electrical and Electronic</td>
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<tr>
<td>EMAS</td>
<td>Eco Management and Audit Scheme</td>
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<tr>
<td>Fire-LCA</td>
<td>LCA model modified to include fires</td>
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<tr>
<td>FR</td>
<td>flame retardant</td>
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<tr>
<td>ISO</td>
<td>International Standardisation Organisation</td>
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<tr>
<td>KCL-ECO</td>
<td>A specialised LCA software developed by KCL, Finland</td>
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<tr>
<td>LCA</td>
<td>Life-Cycle Assessment</td>
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<td>LCI</td>
<td>Life-Cycle Inventory</td>
</tr>
<tr>
<td>MSW</td>
<td>Municipal Solid Waste</td>
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<tr>
<td>NOx</td>
<td>Nitrogen Oxides</td>
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<tr>
<td>PAC</td>
<td>Polycyclic aromatic compounds</td>
</tr>
<tr>
<td>PAH</td>
<td>polycyclic aromatic hydrocarbons</td>
</tr>
<tr>
<td>PBDE</td>
<td>Polybrominated diphenyl ether</td>
</tr>
<tr>
<td>PCDD/F</td>
<td>Polychlorinated dibenzodioxins and furans</td>
</tr>
<tr>
<td>PTFE</td>
<td>Polytetrafluoroethylene</td>
</tr>
<tr>
<td>SCR</td>
<td>selective catalytic reduction</td>
</tr>
<tr>
<td>SNCR</td>
<td>Selective Non-Catalytic Reduction</td>
</tr>
<tr>
<td>TBDD</td>
<td>2,3,7,8-tetrabromodibenzo-(p)-dioxin, in text refers to TBDD-equivalents unless otherwise stated</td>
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<tr>
<td>TCDD</td>
<td>2,3,7,8-tetrachlorodibenzo-(p)-dioxin, in text refers to TCDD-equivalents unless otherwise stated</td>
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<tr>
<td>URF</td>
<td>Unit Risk Factor</td>
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<tr>
<td>VOC</td>
<td>volatile organic compounds</td>
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1 Introduction

Environmental issues are a vital part of our society and the ability to perform accurate estimates and evaluations of environmental parameters is a vital tool in any work to improve the environment. Initially, environmental studies were mainly focussed on the various emission sources, such as factory chimneys, exhaust gases from vehicles, effluents from factories etc. However, in the 1980’s it became apparent that a simple measurement of an emission did not provide a full picture of the environmental impact of a specific product or process. The emissions from a chimney, for example, only reflect one of several process steps in the production of a specific product. To fully describe the environmental impact of a product or activity, the entire process chain has to be described including raw material extraction, transports, energy and electric power production, production of the actual product, the waste handling of the product etc. There was, therefore, an obvious need for a new methodology and an analytical tool able to encompass this new situation. The tool that was developed during this period (end of 1980’s and 1990’s) was: Life Cycle Assessment (LCA).

However, the Life Cycle Assessment methodology also needs continuous improvements to incorporate new aspects and processes. An LCA typically describes a process during normal operation and abnormal conditions such as accidents are left out of the analysis, usually due to lack of a consistent methodology or relevant data. For example, LCA data for power production usually assume normal conditions without any accidents. Provisions for certain accidents in the analysis of the life-cycle could be included provided these could be specified in sufficient detail and occurred with sufficient regularity to make their inclusion relevant.

In traditional LCA models a higher fire performance is only included as a change in energy and material consumption and no account is taken of the positive effect of higher fire performance in the form of fewer and smaller fires. The emissions from fires contribute to the environmental impact from products and should be included in a more complete evaluation of the environmental impact of a product where the fire performance is an important parameter. In cases where the fire performance is not a critical product performance characteristic (e.g underground piping) one should not include this in the product LCA.

This guideline describes a methodology for the incorporation of fires into a Life Cycle Assessment. Fires occur often enough for statistics to be developed providing necessary information on material flows in the model. A model has been specifically developed to allow for this inclusion and will be referred to as the Fire-LCA model. The model itself is generally applicable, provided that appropriate additions and changes are made whenever a new case is studied. To date, the examples that have been analysed are related to building contents and not to building materials. Therefore, the guidelines are more fully developed for building contents applications although this does not exclude their application to building materials.

The Fire-LCA method was originally developed by SP and IVL\textsuperscript{1, 2} and they have since applied the model to three different case studies\textsuperscript{3, 4, 5, 6, 7, 8, 9, 10, 11}. The guidelines given in this report are based on the experience gained during development of the model and its application to the case studies. The completeness of the guidelines was tested in this project by researchers at VTT with previous experience of traditional LCA methodology and knowledge of fires but no previous experience of the Fire-LCA methodology, who used the guidelines to conduct a small test Fire-LCA study. The test case is presented in Appendix C.
2 Life Cycle Assessment (LCA) – the basic concept

Life Cycle Assessment (LCA) is a versatile tool to investigate the environmental impact of a product, a process or an activity by identifying and quantifying energy and material flows for the system. The use of a product or a process involves much more than just the production of the product or use of the process. Every single industrial activity is actually a complex network of activities that involves many different parts of society. Therefore, the need for a system perspective rather than a single object perspective has become vital in environmental research. It is no longer enough to consider just a single step in the production. The entire system has to be considered.

The Life Cycle Assessment methodology has been developed in order to handle this system approach. A Life Cycle Assessment covers the entire life cycle from “the cradle to the grave” including crude material extraction, manufacturing, transport and distribution, product use, service and maintenance, recycling and final waste handling such as incineration or landfill. In a life cycle assessment a mathematical model of the system is designed. This model is a representation of the real system with various approximations and assumptions. With LCA methodology it is possible to study complex systems where interactions between different parts of the system exist to provide as complete a picture as possible of the environmental impacts of, for example, a production process.

Applications for an LCA can be many and some are listed below, divided into internal and external use for an organisation:

Internal
Knowledge generation
Strategic planning
Forecasting
Development of environmental strategies
Environmental improvement of the system
Design, development and optimisation of products or processes
Identifying critical processes for the system
Development of specifications, regulations or purchase routines
Environmental audit
Waste management
Environmental management systems (EMAS, ISO 14000)

External
Environmental information
Environmental labelling
Environmental audit of companies

An LCA usually evaluates the environmental situation based on ecological effects and resource use. In a few cases the work environment has also been included. A traditional LCA does not cover the economic or social effects.

International standards for LCA methodology have been prepared by the International Organisation for Standardisation (ISO). The following standards are available today;

Principles and framework (ISO 14040)\textsuperscript{12}
Goal and scope definition and inventory analysis (ISO 14041)\textsuperscript{13}.
Life cycle impact assessment (ISO 14042)\textsuperscript{14}  
Life cycle impact interpretation (ISO 14043)\textsuperscript{15}.

Generally the method can be divided into three basic steps with the methodology for the first two steps relatively well established while the third step (Impact assessment) is more difficult and controversial. The first two steps are usually referred to as the life cycle inventory (LCI) and can be applied separately without the following impact assessment. In addition to the different steps in the procedure there can also be an interpretation phase. The three basic steps are shown in Figure 1 below.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{The main phases of an LCA according to the ISO standard\textsuperscript{12}.}
\end{figure}

The goal and scope definition consists of defining the study purpose, its scope, system boundaries, establishing the functional unit, and establishing a strategy for data collection and quality assurance of the study. Any product or service needs to be represented as a system in the inventory analysis methodology. A system is defined as a collection of materially and energetically connected processes (e.g. fuel extraction processes, manufacturing processes or transport processes) which perform some defined function. The system is separated from its surroundings by a system boundary. The entire region outside the boundary is known as the system environment.

The functional unit is the measure of performance, which the system delivers. The functional unit describes the main function(s) of the system(s) and is thus a relevant and well-defined measure of the system. The functional unit has to be clearly defined, measurable, and relevant to input and output data. Examples of functional units are "unit surface area covered by paint for a defined period of time," "the packaging used to deliver a given volume of beverage," or "the amount of detergents necessary for a standard household wash." It is important that the functional unit contains measures for the efficiency of the product, durability or lifetime of the product and the quality/performance
of the product. In comparative studies, it is essential that the systems are compared on the basis of equivalent functional unit.

Other important aspects to consider in the goal and scope definition include:

- whether the LCA is complete or if some component is excluded from the study,
- which type of environmental impact is considered in the study, and
- a description of other important assumptions.

In the inventory analysis the material and energy flows are quantified. The system consists of several processes or activities e.g. crude material extraction, transport, production and waste handling. The different processes in the system are then quantified in terms of energy use, resource use, emissions etc. Each sub-process has its own performance unit and several in- and outflows. The processes are then linked together to form the system to analyse. The final result of the model is the sum of all in- and outflows calculated per functional unit for the entire system.

The most difficult part and also the most controversial part of an LCA is the impact assessment. So far, no standard procedure exists for the implementation of an entire impact assessment. However, the ISO standard covers the so called Life Cycle Impact Assessment (LCIA)\(^4\), where different impact categories are used and recommendations for Life Cycle Interpretation\(^5\). Transparency of the LCA model is however important and inventory data must also be available in addition to aggregated data. Several methods/tools have been developed for impact assessment and the tools can usually be integrated with different LCA computer softwares. The modern tools today usually include a classification and characterisation step where the different parameters e.g. emissions are aggregated to different environmental classes such as acidification, climate change or eutrophication. There are of course also possibilities for direct evaluation/interpretation of the different emissions or environmental classes.
3 Methodology – an overview

The Life-Cycle Assessment methodology that has been used in this guideline is based on traditional LCA methodology. This methodology is described in the ISO standard 14040-series and other documents from different countries in Europe and the USA. Different documents have been published in different countries but the basic theories are relatively similar. In the Nordic countries for example the "Nordic Guidelines on Life-Cycle Assessment" (1995) has been publish as a guideline, not a standard. The LCA model including fires has been called the “Fire-LCA” model and will be referred to as such forthwith.

3.1 The risk assessment approach

In a conventional LCA the risk factors for accidental spills are excluded. In the LCA data for the production of a chemical, for example, only factors during normal operation are considered. However, there can also be, for example, emissions during a catastrophic event such as an accident in the factory. Those emissions are very difficult to estimate due to a lack of statistical data and lack of emission data during accidents. The same type of discussion exists for electric power production in nuclear power plants.

In the case of the evaluation of normal household fires the fire process can be treated as a commonly occurring activity in the society. The frequency of fire occurrences is relatively high (i.e. high enough for statistical treatment) and statistics can be found in most countries. This implies that it is possible to calculate the different environmental effects of a fire if emission factors are available. Statistical fire models can be set up for other types of fires but the uncertainty in the statistical fire model will increase as the statistical data is more limited.

The fundamental function of a better fire performance is to prevent a fire from occurring or to slow down the fire development. Improving a product’s fire performance will thus change the occurrence of fires and the fire behaviour. By evaluating the fire statistics available with and without different types of fire performance improvements the environmental effects can be calculated. The benefits of a higher fire performance must be weighed against the “price” society has to pay for the production and handling of possible additives and/or other ways of production. The LCA methodology will be used to evaluate the application of higher fire performance in society. In this way a system perspective is applied.

3.2 The Fire-LCA system description

A Life Cycle Assessment model should be able to describe the LCA system as defined in the Goal and Scope of the study. In this case it should be able to describe the entire life cycle of a product with different fire performance.

Schematically the LCA model proposed for a Fire-LCA can be illustrated as in Figure 2. The model is essentially equivalent to a traditional LCA approach with the inclusion of emissions from fires being the only real modification. In this model a functional unit is characterised from the cradle to the grave with an effort made to incorporate the emissions associated with all phases in the unit’s life-cycle. Thus, the model includes production of material for the product to be analysed, as well as the production of the
additives if applicable. If possible the model should be designed in such a way that the fire performance can be varied. Furthermore, the model should include production, use and waste handling of the product during its lifetime.

During the lifetime of the products to be analysed, some products will be involved in different types of fires. The Fire-LCA model will therefore include modules to describe the fire behaviour for the different types of fires. Fire statistics are used to quantify the amount of material involved in the different types of fires. In addition, the model should also include modules for handling the production of replacement materials that are needed due to the shortening of lifetime that the fires have caused. If possible the model should also include modules for the handling of the fire extinguishing process and the decontamination process.

![Diagram of the LCA model](image)

**Figure 2  Schematic representation of the LCA model.**

A wealth of statistics is available concerning fires from a variety of sources (such as, Fire Brigades and Insurance Companies). Differences between countries and between different sources of data in the same country provide information concerning the frequency of fires and their size and cause. The use of these fire statistics is discussed in more detail in chapter 4.3.
4 Fire-LCA Guidelines

The choices below provide the framework for a Fire-LCA. They should not be seen as insurmountable boundaries but as guidelines. Typically the system boundaries may be defined in different ways and the effect of this definition can be important for our understanding of the model.

4.1 Goal and Scope

The aim of the model is to obtain a measure of the environmental impact of the choice of a given level of fire safety. Implicit in this model is the fact that to obtain a high level of fire safety some fire performance improvement measures need to be taken, these could be for example the addition of flame retardants (FR) or a fire extinguishing system or to change the design of the product. In order to assess the environmental impact of the different levels of fire safety it will be necessary to compare at least two examples of the same functional unit: one with lower fire safety and one with higher fire safety. The model does not necessarily aim to obtain a comprehensive LCA for the chosen functional unit. In other words only those parts of the model that differ between the different versions of the product will be considered in detail. All other parts can be studied in sufficient detail to obtain an estimate of the size of their relative contribution.

4.1.1 Functional unit

The functional unit should include the actual function of the product or service to be analysed. It is also important that the functional unit contains measures for the efficiency of the product, durability or lifetime of the product and the quality/performance of the product. In a Fire-LCA model where the fire performance of a product or a process is evaluated the actual function of the fire protection system could be how well the fire protection works or the number of fire occurrences for a given fire protection system.

However, it can be very difficult to find relevant measures for such an approach. Experience from previous applications of the model has shown it is appropriate in a Fire-LCA to follow the life cycle of the product whose fire performance is studied, as the functional unit during its entire lifetime. Thus, in this case one or a number of products are chosen as the functional unit. A practical method can be to choose the number of products originally produced at the factory and then follow the products throughout their lifetime. In many cases it can be practical to choose a relatively large number of products that e.g. represent the European or a specific country production during a year. Functional units that have been used in previous studies have been e.g. 1 million TV sets or 1 million sofas. In comparative studies such as the Fire-LCA, it is also essential that the systems are compared on the basis of equivalent functional unit.

4.1.2 System Boundaries

A schematic model of a Fire-LCA has already been described in Figure 2. The figure shows the main components of the model and thus also the system boundary. The main parts to be included in the model should be as follows:

- Production of materials and fuels to be used in the product production.
- Production of the fire protection system.
• Production of the product to be analysed (defined as the primary product).
• Use of the primary product.
• Waste handling of the primary product including
  - Landfill
  - Incineration
  - Recycling

• Fire modules describing:
  - Fires starting at primary product and spread to surrounding products (defined as secondary products). These fires are called primary fires. Fires starting at secondary product and spread to primary product. These fires are called secondary fires.
  - Waste from fire activities including
    - demolition
    - decontamination
    - landfill, incineration, recycling

• Additional production of primary products for replacement of primary products that have been lost in fires.
• Production of secondary products for replacement of secondary products that have been lost in primary fires spreading to secondary products.
• Fire extinguishing activities.
• Landfill fires in the landfilled materials.

This represents a comprehensive list of the processes involved in fires. In practice it is sometimes not possible to include all of the above activities.

According to standard practice no account should be taken of the production of infrastructure such as construction of plants for production of chemicals etc. or impact due to personnel. Concerning the features of the model that are specifically related to fires the system boundaries should be set such that they do not appear contrived. In general, it is realistic that we assume that material that is consumed in a fire would be replaced. Where possible, one should rely on literature data to ascertain the size of such contributions. In lieu of such data an estimate of the contribution should be made based on experience of similar systems. In the case of small home fires, which are extinguished by the occupant without professional help, the mode of extinguishment is not included due to the difficulty in determining the extinguishing agent. In cases where the fire brigade is called to a fire, transport and deployment should be included as realistically as possible. In the case studies performed so far using the Fire-LCA model, however, neither extinguishment activities nor landfill fires have been assessed.

### 4.1.3 Parameters to be considered – Resources, energy, emissions and waste

A Fire-LCA study follows the same criteria as a traditional LCA study concerning the parameters to be considered in the analyses. Thus, the parameters used are based on

• Energy use
• Resource use
• Emissions and
• Waste
In the case of fire the emissions are of greatest interest. A wide variety of species are produced when organic material is combusted. The range of species and their distribution is affected by the degree of control afforded in the combustion process. Due to its low combustion efficiency a fire produces much more unburned hydrocarbons than does controlled combustion. In the case of controlled combustion one would expect that carbon dioxide (CO₂) and water (H₂O) emissions would dominate. In a fire, however, a wide variety of temperature and fuel conditions and oxygen availability produce a broader range of chemical species, such as CO, polycyclic aromatic hydrocarbons (PAH), volatile organic compounds (VOC), particles, and dibenzodioxins and furans etc. Exactly which species should be considered depends on the materials involved in the evaluated product, for instance if the product does not include any bromine in itself or during the production cycle then brominated species can be excluded.

4.1.4 Other model parameters and scenarios formation

An LCA model contains not only information concerning resource uses and different emissions but also of e.g. different types of fire protection, waste handling procedures or recycling scenarios. In LCA models there is also information concerning different transports and generation of electric power for the various modules. In most applications of an LCA it is common to propose a variety of scenarios and to investigate the effect of the choices involved. In many cases the different scenarios chosen reflect the waste handling used today and anticipated waste handling in the future. Other scenarios might reflect use of different statistical fire models. Indeed, due to a lack of detail in much of the available fire statistics it will often be necessary to postulate a number of best and worst case fire models to determine the robustness of the results.

4.2 Special Fire Considerations

In the Fire-LCA model, the terms “primary fires” and “secondary fires” have special meaning that may differ from the terminology used elsewhere. Thus, they are defined here as follows:

Primary fires
Primary fires are fires starting in the primary product, i.e. the functional unit. These fires can spread to also involve the entire room or the entire building.

Secondary fires
Secondary fires are fires starting in some item other than the functional unit which spread and ultimately involve the functional unit.

In the Fire-LCA model fires are included as a possible end of life scenario before the normal end of life, i.e. the fire shortens the lifetime of the product. The products that end their lives in this way can either start the fire themselves or be consumed in a fire that has originated elsewhere. The case where the product starts the fire is referred to as a “primary fire” in this model and this fire can then spread to involve other items. Fires, which originate from other items are referred to as “secondary fires”.

The primary fires have been divided into four categories in the case studies conducted so far, i.e.:
• small fire in product only, results in no emissions, i.e., only replacement of the product,
• larger fire involving the product only, results in product replacement and inclusion of fire emissions from the burning product,
• fire involving entire room, results in fire emissions from the room (including the product) and replacement of both the product and room contents, and
• fire involving the entire dwelling or building, results in emissions from burning the entire dwelling or building and replacement of the entire dwelling or building.

This grouping is probably appropriate for most fires in building contents, but changes probably needs to be done if building materials, industrial fires, etc. are evaluated

There is only one category of secondary fires. Emissions from burning the product and the replacement of the product should be included for the secondary fires. All other material involved in secondary fires is not included in the environmental load of this occurrence. The emissions in this case are the emissions from the product alone, in many cases burning in a flashed over room.

4.3 Statistical fire model

The number of products that are involved in the different types of fires constitutes the fire model. The fire model should preferably be based on fire statistics but could also, if there are no statistics available, be based on some hypothesis and perhaps comparison to other similar products where statistics are available.

The fire statistics that are used to develop the fire model must be detailed. One must be able to determine the number of primary and secondary fires each year. In addition one must be able to estimate the size of these fires, i.e., the number of fires that grow to involve the rest of the room and/or the rest of the building. Fire statistics tend only to include fires that are large enough for the fire brigade to be summoned. In many cases small fires are extinguished by people nearby and the fire brigade is not called. These fires are, however, often reported to insurance companies as part of an insurance claim. Therefore statistics from insurance companies should also be included in construction of the fire model.

The number of fires differs in many cases significantly between different countries. This depends on method of reporting the statistics together with cultural and possibly geographical differences. In addition, the number of fires in a country change over time due to changes in regulations or in lifestyle e.g. proportion of smokers, use of certain equipment such as smoke detectors, etc. Therefore care must be taken when choosing which statistics are used to construct the fire model. In addition, there are always stochastic differences between different years and thus the calculations should not be based on statistics from a single year.

The Fire-LCA model is suitable for investigating the effect of different fire regulations. In this case there are three possibilities;

a) Comparisons are made within one country, where the regulations have been made stricter
b) Comparisons are made between two countries, where regulations are different, i.e. one county has stricter rules than the other
c) Comparisons are made within one country where stricter regulations are proposed but have not yet been implemented.
In case a) statistics exist for the time period before the stricter rules were applied and after. Usually, when a change in regulations is implemented all old equipment is not thrown away but is changed gradually and products with higher fire performance will coexist with products with a lower fire performance for a period of time. The rate at which products are changed into newer products depends on the lifetime of the product. The most commonly used distribution of lifetime is the exponential distribution with the survival function \( R(t) \)

\[
R(t) = e^{-\lambda t} = e^{-1/\text{lifetime}}
\]

where \( t \) is the time. The percentage of the product in use based on the old regulations is calculated from the survival function and that percentage is then used to calculate the number of fires that would occur if all products where based on the old regulations and if all were based on the new rules. If market evaluations are available which show how many old products and new products that are currently in use then these numbers can be used instead of the ones obtained from the above survival function calculation.

In case b) it is important to choose statistics from two countries that are culturally and construction-wise as similar as possible and to carefully investigate the differences that exist in the method of reporting statistics and lifestyle of people in the countries chosen.

In case c) no statistics are available. In this case one has to use the statistics from the country in which the regulations are about to be changed and then estimate what the statistics would be if the regulations were adopted. This estimation can be made from experiments where one tests ignitability and flame spread properties of the product constructed based on the new regulation compared to those for the product according to the old regulations, or experience from previous regulations on similar products, if such exist.

Another application of the Fire-LCA model is to compare two products with different fire performance regardless of the regulations. This places extra demands on the details available in the statistics. In this case, one must be able to distinguish the different types of the product in the statistics. If this is not possible then one has to estimate the fire frequencies in the different types of the product. However, if the two types of the product can be assumed to have the same fire performance then one uses the same fire frequencies for both types.

In cases when a series of assumptions have been made in order to set up the statistical fire model it is prudent to run the Fire-LCA analysis using several statistical fire models in order to conduct a sensitivity analysis. Further, it is imperative that the assumptions are clearly defined in the model presentation to facilitate a critical evaluation of the results.

4.4 Replacement of burned materials

A fire can be considered to be a process where the lifetime of a product is shortened. Thus, the product has to be replaced earlier than the average. This results in an increased production with a corresponding increase in energy use and emission release. Lifetime distributions often follow the bath tub curve with many faults in the beginning of a product's lifetime due to manufacturing faults and then again many faults when the product is approaching the natural end of its life cycle. As an average, however, a 50% reduction of the lifetime can be assumed if no information is available on the fire distri-
bution over a products lifetime. To reflect this reduction of lifetime it is assumed that only 50% of the burned material is replaced.

The replacement of burned material should not only comprise the actual product to be analysed but all material involved in the fire, for example material in the room or in the house that is also involved in primary fires. From the fire statistics the number of fires in the particular product and the fire spreading are derived. This information gives the number of products and surrounding materials to be replaced due to the fires. In the model this will result in an increased amount of products produced that are analysed and also a production of replaced materials due to fire spread beyond the functional unit in the LCA. Thus, the model must include LCA production modules for production of a house and the interior materials that are involved in the fires.

In the previous Fire-LCA studies performed by IVL and SP the fire spread beyond the functional unit has been divided into room fires and house fires (entire house) due to the organisation of the fire statistics. Thus, LCA modules for production of a house and interior materials have been included in the Fire-LCA model. The amount of interior materials reflects in these cases an ordinary house and also the materials in the room fire tests. In the cases conducted thus far LCA data for a house with 121 m² has been used¹⁷ for the replacement of the building material of the entire dwelling. A typical/standard lounge room area of 16 m² has been assumed (assuming that a 3 room flat has an area of 80 m² and dividing this with 3 rooms+kitchen+bathroom). For the room fire case an area allocation has been used. The room fire replacement of building materials contribution has thus been assumed to be 16/121 of the house. The same approach has been used for replacement of building contents and interior material. It is assumed that a typical room contains the same proportion of wood, paper, textiles, PVC, PUR and polyethene as the entire dwelling¹⁸, and no special calculations have been made for atypical rooms such as the kitchen or laundry. The amount of the different materials used for the design of the fire room experiments and replacement of burned materials is listed in Table 1. These have been calculated assuming a fire load of 720 MJ/m²¹⁹,²⁰ which corresponds to a material density of 40 kg/m² floor area assuming an average heat of combustion value 18MJ/kg¹.

<table>
<thead>
<tr>
<th>Material</th>
<th>Dwelling (121 m²)</th>
<th>Room (16 m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wood</td>
<td>2780</td>
<td>368</td>
</tr>
<tr>
<td>Paper</td>
<td>720</td>
<td>95</td>
</tr>
<tr>
<td>Textiles</td>
<td>720</td>
<td>95</td>
</tr>
<tr>
<td>PVC</td>
<td>240</td>
<td>32</td>
</tr>
<tr>
<td>PUR</td>
<td>240</td>
<td>32</td>
</tr>
<tr>
<td>Polyethene</td>
<td>100</td>
<td>13</td>
</tr>
</tbody>
</table>

### Table 1 Amount of different types of burnable material in a dwelling and room respectively (kg).

#### 4.5 Data Inventory

In the inventory analysis the material and energy flows are quantified. An important aspect in the inventory analysis is the model resolution. The model resolution can be

¹ The combustible material used in the room experiments in the TV study has later proved to be less than 40 kg/m² but should be 40 kg/m² in order to reflect the values obtained in the CIB work²⁰.
expressed as the smallest unit that can be resolved in the analysis. The resolution requirements are determined by the ultimate evaluation. In many cases the evaluation includes an evaluation of different fire protection systems e.g. use of different flame retardants. This requires a high resolution of the composition of the product materials, usually plastic materials. The resolution and quality of the model must be so high that the composition of the materials can be varied and the result can be evaluated. This can usually be considered as a high resolution for an LCA.

Furthermore all relevant emissions have to be covered as well as the use of raw materials and energy resources.

### 4.5.1 Material, product production and product use

In a Fire-LCA it is useful to divide the different materials used in a product into flame retardants and other materials used in the product. This distinction makes it easy to analyse and vary the different types of fire protection systems. The two groups can also be aggregated and classified in the LCA model to simplify the analysis. It is also advised that the model is designed in such a way that the composition/concentration of the flame retardant can be varied. Other materials can be handled in the same way as in a traditional LCA.

The different materials and components are then put together in a production process to form the final product to be analysed. In some cases the design of a product can include fire protection. This can result in a more difficult product to produce. This aspect can be included in the product production module. Otherwise, the production can be handled as in a traditional LCA.

Sometimes the use of a product can include environmental aspects such as use of electric power of a TV set during its lifetime. This also has to be included in the model and this is included in the Product Use Module.

### 4.5.2 Waste handling

The waste handling procedures may have a major influence of the overall result of an analysis. The type of fire performance improvement system used must be reflected in the waste modules. The influence of, e.g., a flame retardant on all the different waste handling alternatives must be included. Thus, the resolution requirements for the model are also high for the waste modules. The calculation of data for the waste handling modules is usually difficult and requires some estimation in cases where full data is not available. The calculations may also include allocation difficulties. Detailed information on LCA input data from waste handling of flame-retardants is given in appendix A.

### 4.5.3 Fire emission data

Literature data on fire emissions can be used if available. The emissions should be detailed and preferably include e.g. CO, CO₂, HCN, NH₃, HCl, NOₓ, HBr, VOC, PAHs, isocyanates, chlorinated and brominated dioxins and furans. However, if the products evaluated do not, for example, contain any phosphorus then the phosphorous containing species can be excluded. Similarly, if the product contains any specific additives then these must be included in the measurement together with possible products when this
additive burns, for example if the product contains any brominated FR then the specific FR in question and brominated dioxins and furans should be considered.

If literature data is not available then experimental data should be obtained. The fire experiments should provide as realistic input data as possible to the Fire-LCA model. Preferably one should conduct at least one test for each type of fire in order to obtain a good estimate of the emissions from the fires. Fire experiments and the analyses needed to measure the emissions are, however, costly and therefore the number of experiments must be optimized. The fire experiments should give required input to the primary fires (confined to the functional unit, confined to the room of origin or confined to the house of origin) and the secondary fires (in this case relating to the emissions from the functional unit only).

4.5.3.1 Primary fire, product only

For the case of a primary fire that only involves the product an experiment should be set up such that the entire product is consumed in the fire. Typical ignition sources for primary fires are cigarettes, matches and candles. It is often not possible to ignite a product with a high fire performance using a small flame. However, the statistics may indicate that these fires occur. These fires can usually be explained in that there is some other material involved in the fire as well, for instance a blanket or cushion in a sofa. In those cases the primary fire experiments need to be conducted using a larger ignition source such as larger burner or a pool fire. In these cases the emissions from the ignition source (essentially only CO₂) should be subtracted.

4.5.3.2 Primary room and house fire

For the primary fire that spreads to involve the room an experiment should be set up where an entire room is consumed in a fire, which starts in the product evaluated. The room should preferably reflect a typical room in which one usually finds the product. If, for instance, a TV or video is evaluated then the room should be a living room. If one evaluates a fridge then the room should be a kitchen. In some cases it is difficult to determine the surroundings of a product. Take for instance a washing machine; this can either be situated in the bathroom, the kitchen or a laundry. The contents of these rooms differ somewhat but there are some similarities, i.e. there are no upholstered furniture or bookshelves, there are several machines present i.e. one or several of: tumble dryer, dishwasher, stove, fridge etc. This makes it possible to construct a model environment.

For the entire house/dwelling case a similar approach is preferred, i.e. a fire experiment starting in the product evaluated spreads to involve the entire dwelling. Fire experiments involving an entire dwelling are, however, usually too expensive or logistically difficult to conduct due to the large heat release rate. Instead one must extrapolate from the room experiment. In the studies conducted thus far, in order to estimate the emissions from a full house fire from experimental data for room fires, the emissions from a full room experiment has been presented as emissions per square meter and scaled up to the full area of the model house. The basis for this is that the material content is approximately the same in all types of rooms, i.e. amount of plastic, wood, etc. as presented in Table 1, and that the room experiment is designed accordingly. The scale up is done on an area basis using an area of 16 m² for a typical room and 121 m² as a typical house. In the case studies conducted to date the product evaluated has been situated in a living room. The fire load has been chosen as 40 kg/m², which corresponds to a fire load of 720 MJ/kg².
The fire emissions from the building materials in the room and dwelling have not been included in the analysis.

### 4.5.3.3 Secondary fires

For the secondary fires the emissions from the product in a burning room should be measured. It is not possible to distinguish the amount of emissions due to the product and the amount due to the other burning items if one measures the emissions from a burning room. Instead one has to set up an experiment where the product is subject to similar radiation and heat as in a burning room. This requires large burners and that the product is contained in an empty room. But care must be taken so that the walls of the room do not give any emission during the experiment.

### 4.5.3.4 Reducing the number of experiments

In many cases one cannot run the full set of 4 experiments per product (three primary and one secondary) described above due to budget limitations. If the number should be reduced then one has to make sure that the types of fires that are most common according to the statistical fire model set up are simulated most accurately and the types of fires not simulated are estimated from the data obtained from the experiments. For instance, primary fires are more common for products with lower fire performance than for those with higher fire performance while the number of secondary fires is the same independent of fire performance. This means that in many cases it is more important to simulate the secondary fire for the product with higher fire performance and the primary fires for the product with lower fire performance. How to estimate the types of fires that are not directly simulated in the experiments differs depending on the type of experiments that have been conducted, examples of different solution are given in Appendix B.

### 4.6 Competences needed to conduct a Fire-LCA analysis

Since a Fire-LCA analysis involves several different aspects it is usually not possible for one person to conduct such a study. The people involved in the process must have competence within LCA, fire statistics and other statistics, fire experiments, emission data sampling and analysis and detailed knowledge of the production processes for the product evaluated is essential. Therefore a group must be formed to cover all these areas of expertise.
5 Evaluation of results

The most difficult, and also the most controversial, part of an LCA is the Impact Assessment. No single standard procedure exists for the implementation of impact assessment although generally different methods are applied and the results compared.

In the valuation phase, the different impact classes are weighed against each other. This can be done qualitatively or quantitatively. Several evaluation methods have been developed. The methods that have gained most widespread acceptance are based on either expert/verbal systems or more quantitatively methods based on valuation factors calculated for different types of emissions and resources such as Ecoscarcity, Effect category method (long and short term), EPS- system, Tellus, Critical volume or Mole fraction. Due to the fact that many important emission species from fires (in this particular study: dibenzodioxins and furans, and PAH, etc.) are either not dealt with in detail or not available at all, these methods are not suitable for an objective interpretation of environmental impact in the Fire-LCA application. Thus, a qualitative comparison method has been found to be most beneficial.

In some cases, the LCA analysis is followed by an interpretation phase where the results are analysed. This phase provides an opportunity for the discussion of the results in terms of safety aspects. The fact that people may die in fires and that products with higher fire performance cause a reduction in the number of fire deaths cannot be included explicitly in the LCA. This can however be discussed together with the results of the LCA analysis to provide a context for their interpretation and a connection to the reality of fire safety.

In the Fire-LCA studies conducted to date the emphasis has been on emissions to air while emissions to water and soil have only been discussed briefly. The evaluation has been based on comparisons between the different cases i.e. high and low fire performance or cable type for different emissions such as CO, CO₂, HCN, PAH, Dioxins, NOₓ, HCl, Antimony, HBr, hydrocarbons, Phosphorous and PBDEs and energy resource use. In addition the environmental effect of two species, i.e. PAH and chlorinated dibenzodioxins, has been discussed based on a comparison between these two species and their cancer risk.

The comparison is based on the assignment of “Unit Risk Factors” (URF) which have been defined according to epidemiological studies. Using this “unit risk” model one can compare the risk that a person exposed to the same quantity of different substances over his/her lifetime would have to develop cancer. Although this model is not directly applicable to the Fire-LCA studies it does provide a method by which the PAH and PCDD/F emissions can be reduced to a common denominator in order to make a coarse comparison between their relative importance. This relative importance is of interest due to the fact that TCDD/TBDD equivalents typically receive most attention as environmental toxins while, in many applications of the Fire-LCA model, PAH may actually pose the greatest environmental danger.

One should, further, keep in mind that while the LCA model is based on information from single fire experiments the emission results are not point emissions but total emissions over the whole life cycle of the product evaluated. Thus, the application of a general exposure model is not entirely inappropriate.

The application of the Unit Risk Factor model requires that the PAH emissions be reduced to a single toxicity equivalence factor in essentially the same manner as for the TCDD and TBDD equivalents. In the case of PAH the most toxic species to which all
other species are reduced is benzo(a)pyrene, or BaP\textsuperscript{22}. This species has been defined as the most toxic species and assigned a toxic equivalence factor of 1 in the same way that 2,3,7,8-tetrachloro-dibenzodioxin (2,3,7,8-TCDD) is defined as the most toxic of the polychlorinated dibenzodioxins and furans. All other species are then assigned toxic equivalence factors relative to BaP, allowing the calculation of BaP-equivalents. BaP is 20 times less carcinogenic than the species 2,3,7,8-TCDD, the unit risk factor is 0.07 \( \mu \text{g/m}^3 \) for BaP and 1.4 \( \mu \text{g/m}^3 \) for 2,3,7,8-TCDD (the species).
6 Adding fire modules to an existing LCA model

Fire-LCA data can be added to an existing LCA for any given product. In this case several steps are important to ensure correct determination of the environmental impact of the fires the product could potentially be involved in during it’s life cycle. The following steps are important in an expansion of a traditional LCA treatment:

- Determine the relevant fire model as outlined in section 4.3
- Determine which fire categories require emissions data
- Investigate whether fire emission data is available in the open literature or needs to be determined through specific fire experiments
- Establish how the flow of the functional unit is affected by the inclusion of a certain number of products in fires. This can require some recalculation of the original LCA treatment although existing LCI data should be unchanged.
- Determine which end-of-life scenarios are relevant (if these are different to those dealt with in the traditional treatment).

Once these points have been covered the traditional LCA provides a sound basis for a Fire-LCA model requiring little adjustment.
7 Computer modelling methods

Different computer software solutions for LCA calculations exist. Generally the software can be divided into two different groups:

- Specific Life Cycle Assessment programs, (KCL-ECO, LCA Inventory Tool, SimaPro etc.), and,
- General calculation programs such as different spread sheet programs (Excel etc.).

In addition to the different LCA calculation programs several database structures for storage of LCA data and meta-data exist.

Experience from previous Fire-LCA projects have shown that the use of a specific LCA software is a great advantage compared to other more general calculation software. Specific LCA software is a versatile tool for performing LCA studies. With LCA software you can easily build complex LCA system models and calculate results for the system. Such software can handle processes as well as transports and material flows between modules. Flows can be feedback connected and it is therefore easy to handle material recycling processes. LCA software is basically a program for solving linear equation systems. Non-linear processes can usually not be calculated in these programs. If necessary, non-linear processes can be calculated separately in other programs and inserted as constants.

Specific LCA programs usually also contains modules for impact assessment calculations often with options for the calculation of classification and characterisation data. It is also possible to include sensitivity analysis and different valuation methods based on valuation factors such as Ecocarcity, the Effect Category Method and the EPS-system.

In addition, there are also LCA models developed for specific purposes that can be used in e.g. the inventory phase to calculate data for specific modules/processes. Example of this type of models can be LCA models for waste management (landfill, incineration, recycling). Many LCA studies in different areas are based on such specific models. However, they are generally not public software but can be used and modified in co-operation with the author/designer. Example of softwares for waste management is ORWARE\textsuperscript{23}, MIMES/Waste\textsuperscript{24}, NatWaste\textsuperscript{25}, the fms\textsuperscript{26} waste management model, LCAiT waste management applications\textsuperscript{27} and EASEWASTE\textsuperscript{28}. 
8 Simplified approach

The full Fire-LCA (indeed any full LCA) requires considerable effort with the determination and collection of suitable LCI data being the most time consuming part of the study. In some cases a simplified approach could be preferable to the full LCA model approach in order to save time and money.

Several simplification alternatives exist that can still provide an indication of the relative environmental impact of, for example, a certain flame retardant treatment relative to that of the fires one avoids through the construction of high fire performance products. Common to all simplifications suggested here is that they only provide relevant information if they are used as a part of a comparison, i.e., between two alternative design approaches to the same product.

8.1 Background minimisation

In this approach, all parts of the model that are the same in the two design approaches used in the comparison are excluded. This approach has the advantage that LCI requirements are generally significantly reduced. The main disadvantage, however, is that while one obtains interesting information concerning the relative importance of the specific design choices made one cannot obtain any indication of the relevance of these differences in the context of the total environmental impact of the product during its lifecycle.

This is perhaps best illustrated by considering a simplistic and figurative example of a comparison between product A and B where emission of PAH for those parts of the model that differ only shows that product A emits 10 units of PAH while product B emits only 1 unit PAH (a factor between product A and B of 10:1). Should one include the full LCA data, however, one finds that product A and B have the same PAH emission (within the certainty of the model) as the background PAH emission from all the similar parts of the model is $10^6$ units, reducing the factor between product A and B to 1:1.

8.2 Parameter minimisation

In both traditional LCA models and the Fire-LCA model one tends to include as many parameters as possible to obtain as detailed a treatment of the product as possible. One includes information concerning both CO, CO$_2$, PAH, acid gases, organic species, energy consumption, etc., emissions to air, water and soil. It is not unusual to have over 1000 variables with a similar number of linear equations describing their interaction. Of these 1000’s of variables only very few are typically included in the final analysis of the environmental impact of the product design choices.

One could potentially reduce the number of species included in the LCI to those species one knows, from experience, are most important in Fire-LCA applications. Experience from applications of the Fire-LCA model to date suggests that large organic species appear to be typically most important in this model. Similarly, if one is most interested in the emissions to air then one could reduce the extent of the model by considering only emissions to the air and not those to water and soil.
8.3 Scenario minimisation

In the applications of the Fire-LCA model conducted to date several scenarios have been investigated. The different scenarios include present day and future waste handling, different degrees of recycling and different interpretations of the fire statistics. These scenarios were chosen in order to investigate the result depending of the assumptions made in the model. In order to save time one can minimize the number of scenarios and investigate, e.g., only one scenario.
9 Limitations

While the Fire-LCA tool provides a good starting point for a holistic interpretation of a realistic life-cycle of a product including information concerning the probability that the product may be involved in a fire it does not provide information concerning, for example, the effect of the toxicity of chemicals used in the product, number of lives saved, costs associated with the different cases or the societal effect of manufacturing practice.
10 Conclusions

Fire-LCA is an LCA method that incorporates fires as one possible end of life scenario. It was developed by SP and IVL in order to be able to assess life cycle aspects of the fire performance of a product. Guidelines have been written in this report on how to perform a Fire-LCA analysis. The guidelines are based on experience gained during the development and application of the Fire-LCA model. These guidelines have also been evaluated by a research group at VTT with prior experience of LCA but no experience of the Fire-LCA method. The test study proved that the guidelines are written in a logical and comprehensive manner and can be used as a starting point by a group of people competent within LCA and fires to perform a Fire-LCA analysis.

A great deal of input data is needed in order to conduct a Fire-LCA study. Very little fire emission data is reported in the literature. Only recently have detailed characterisation of fire emissions been conducted on a more regular basis in some laboratories. Much data is confidential. However, as the number of fire-LCA studies and research on fire emissions increase, such data will become more readily available. It can also be difficult to find production data for some materials, although this problem is common to both Fire-LCA and traditional LCA applications.

While the Fire-LCA tool provides a good starting point for a more holistic interpretation of a realistic life-cycle of a product including information concerning the probability that the product may be involved in a fire it does not provide information concerning, for example, the effect of the toxicity of chemicals used in the product, number of lives saved, costs associated with the different cases or the societal effect of manufacturing practice. The Fire-LCA concept would pose a much more powerful tool if these aspects could be included. This requires that a multivariate analysis method be developed which would potentially assist decision makers to fully evaluate all consequences of a change in regulations, the introduction of a new production method, a new product, etc. Full application of such a model would also require a significant amount of research into the toxicology of many of the emissions analysed within each model application.
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24 MIMES/Waste, Chalmers University of Technology. Contact: Johan Sundberg, Profu, Mölndal Sweden.

25 NatWaste, Chalmers University of Technology., Contact: Maria Ljunggren Söderman, IVL Swedish Environmental Research Institute.

26 fms (Environmental Strategies Research Group), Royal Institute of Technology (KTH), Contact: Göran Finnveden, fms.

27 LCAiT, CIT Ekologik AB. Contact: Elin Eriksson, IVL Swedish Environmental Research Institute.

28 EASEWASTE (Environmental assessment of solid waste technologies and systems) Contact: Thomas H. Christensen, Technical University of Denmark, DTU.
Appendix A Waste handling

Incineration

The objective with the work presented in this chapter is to provide LCA input data regarding waste incineration of materials containing flame-retardants. Thus, this work includes a review of the literature and a method to obtain data not available from the literature.

Waste incineration results in emissions to the atmosphere, contaminated wastewater and contaminated ash. The amounts of waste water generated are generally low. The ash can contain high concentrations of heavy metals and the pollutants present in the ash residues can be significant when placed in landfill sites where leaching may be a source of groundwater contamination. The fly ash also contains significant concentrations of chlorinated dibenzodioxins and furans whereas the bottom ash has been reported to contain negligible amounts1.

Thus, the main focus here will be on the emissions to the atmosphere, where first qualitative information is needed regarding types of primary and secondary emissions formed. Secondly, the quantitative emissions need to be estimated.

The papers in the literature can be divided into the following categories:

- Laboratory investigations on pyrolysis and combustion
- Pilot scale investigations
- Emission measurements in commercial plants

Few data appear to exist regarding the effect of flame-retardants on the emissions from commercial scale waste incineration. Most data concerns fundamental combustion or pyrolysis chemistry that provides qualitative rather than quantitative information. The most relevant study has been performed at the Tamara pilot incinerator in Karlsruhe2. In addition to literature findings, available data from the commercial waste incineration plant in Göteborg is used as input.

The emissions that should be considered are chosen as outlined in section 4.5.3. In combustion of flame retarded materials containing bromine, the emissions of HBr, Br₂ and brominated and/or brominated and chlorinated dibenzodioxins and dibenzofurans needs special attention. The halogens (bromine, chlorine) effect on the gas phase chemistry may also cause higher emissions of unburned hydrocarbons such as CO and VOC (volatile organic compounds).

<table>
<thead>
<tr>
<th>Table A-1  Emissions to consider from incineration.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Major components:</strong> CO₂, H₂O</td>
</tr>
<tr>
<td><strong>Minor components:</strong> CO, NOₓ, N₂O, NH₃, HCN, SO₄, HCl, HBr, Br₂, CH₄, VOC*</td>
</tr>
<tr>
<td><strong>Trace components:</strong> PAC, volatile heavy metals, PCDD/F, PBDD/F</td>
</tr>
<tr>
<td><strong>Particulates:</strong> Ash and soot particles</td>
</tr>
</tbody>
</table>

*VOC = Volatile Organic Compounds
The emissions during combustion depend on both the fuel and the facility where the combustion takes place. The combustion result is governed by the temperature, turbulence (i.e., gas mixing) and time of reaction.

The emissions can be classified as:

- **Product derived emissions**, such as CO₂ and SO₂, where the emissions can be directly related to the chemical composition of the fuel,
- **Process derived emissions**, such as PAH and dibenzodioxins, that are formed under certain conditions from combustion intermediates, and
- **Product and process derived emissions**, such as NOₓ, where the emissions is a result of the primary formation from the fuel nitrogen and the nitrogen in the combustion air and secondary oxidation depending on process conditions.

Below, the various emissions that may be formed are discussed in turn.

**Carbon dioxide, CO₂**
Carbon dioxide forms from the carbon content in the fuel at a proportion that can be assumed equal to the carbon content. In order to estimate the contribution to the enhanced greenhouse effect it is necessary to differ between fossil CO₂ and CO₂ formed from biomass combustion.

**Water, H₂O**
Water forms from the evaporation of moisture and the oxidation of the hydrogen content in the fuel. Water is important for the combustion chemistry and it can be important for the energy balance.

**Carbon monoxide, CO**
CO forms both during the combustion of volatiles and char. In order to get an efficient burnout, the mixing of combustible gases and combustion air, residence time and temperature are important. CO burns with the OH radical and chlorine, bromine and iodine are known to catalyse radical recombination reactions resulting in lower radical concentrations and thus also higher CO emissions.

**Nitrogen oxides, NOₓ (NO and NO₂)**
The main component in combustion is NO whereas NO₂ forms when the combustion gas is cooled in the atmosphere. NOₓ forms mainly from the fuel nitrogen, both from the volatiles and the char. At higher temperatures, molecular nitrogen can also be oxidised according to a mechanism known as prompt NOₓ (>1200 °C) or thermal “Zeldovich” NOₓ (>1400 °C).

The emissions are a result of a number of destruction and formation reactions. By supplying the combustion air in several stages in such a way that sub-stoichiometric zones (low oxygen concentrations and reducing conditions) are created, a substantial amount of the NOₓ primarily formed can be reduced. In order to decrease possible thermal NOₓ, it is common to recirculate part of the flue gas, which apart from cooling the combustion zone also improves the mixing. During devolatilisation, the nitrogen can escape the fuel bed partly as ammonia (NH₃) and hydrogen cyanide (HCN) with a NH₃/HCN ratio depending on the type of fuel. NH₃ and HCN are subsequently oxidised to form a mixture of NO, NO₂, N₂O and N₂. The oxides can be reduced to N₂ under sub-stoichiometric conditions and in addition N₂O decomposes to N₂ if the temperature is high enough (>800 °C). It can be noted that emissions of NH₃ have been observed in plants burning biomass even where a SNCR (see below) system is not used.
In addition to the homogeneous gas phase reduction there are also complicated heterogeneous destruction routes involving char as well as fly ash particles.

NO\textsubscript{x} emissions can be reduced by SNCR (Selective Non-Catalytic Reduction) where solutions containing ammonia or urea are injected into a hot zone in the boiler. A catalyst based system SCR (selective catalytic reduction) can be used at lower temperatures. An ammonia slip of a few ppms is obtained for optimised systems. When urea is used, there is a risk of N\textsubscript{2}O formation.

**Nitrous oxide, N\textsubscript{2}O**
Forms mainly from fuels where the fuel nitrogen is released as HCN and it can also form in SNCR/SCR systems based on urea injection (see nitrogen oxides above).

**Ammonia (NH\textsubscript{3} and HCN)**
See NO\textsubscript{x} above.

**Sulphur oxides, SO\textsubscript{x}**
The emission of sulphur oxides (SO\textsubscript{2} and SO\textsubscript{3}) is governed by the sulphur content in the fuel. The emissions can for instance be reduced by dry lime stone injection or in scrubbers. Some reports indicate that the SO\textsubscript{2} concentration can affect the radical pool and thus also affect the emissions of products of incomplete combustion, such as CO\textsuperscript{7,8,9,10}.

**Hydrogen fluoride, HF**
HF derives from combustion of fluorinated hydrocarbons such as PTFE.

**Hydrogen chloride, HCl and Cl\textsubscript{2}**
Chlorine in municipal solid waste combustion is present as sodium chloride and PVC. The split between HCl and Cl\textsubscript{2} is determined by thermodynamics as well as chemical kinetics. The chlorine will mainly be emitted as HCl, which is efficiently removed in scrubbers. The chlorine also takes part in radical quenching reactions and in the formation of chlorinated hydrocarbons as for instance TCDD/F. Halogens quench the radical chemistry and an increase of chlorine content can result in higher emissions of products of incomplete combustion\textsuperscript{11,12,13,14,15}.

**Hydrogen bromide, HBr, and bromine, Br\textsubscript{2}**
Formation determined by the content of bromine in the waste. The split between HBr and Br\textsubscript{2} is determined by thermodynamics as well as chemical kinetics. In comparison with the Cl\textsubscript{2}/HCl split for chlorine the Br\textsubscript{2}/HBr split will be larger and the emissions of Br\textsubscript{2} can be significant under certain conditions. As stated above, halogens interfere with the radical chemistry. Since bromine is more effective as a flame retardant\textsuperscript{16} it is likely that bromine has a larger effect on the emissions of unburned hydrocarbons as compared to chlorine.

**Hydrocarbons (VOC)**
Methane and hydrocarbons (or VOC - volatile organic compounds) evolve during the devolatilisation of the fuel and if not properly mixed with the oxygen in the combustion air, part of the hydrocarbons may be emitted.

**Polycyclic aromatic compounds, PAC**
PAC are polycyclic ring compounds that consist of two or more benzene rings. A subclass to PAC is polycyclic aromatic hydrocarbons (PAH) where there are no heterocyclic atoms in the ring. To ensure low emissions of polycyclic aromatic compounds efficient combustion conditions are required.
Chlorinated dibenzodioxins and furans, PCDD/F

As discussed in a recent review paper\(^{17}\), the formation of polyhalogenated dibenzodioxins and furans (PHDD/PHDF) in combustion is dominated by heterogeneous synthesis reactions on fly ash particles. Two pathways both occurring around 300 °C are:

1. the precursor synthesis where products of incomplete combustion (PICs), i.e. unburned hydrocarbons, react with chlorine in the gas phase. The precursors can condense on fly ash particles and undergo catalytic reactions to form aromatics.
2. the de novo synthesis, where the carbon source is bound particulate carbon. Chlorination, which can be catalysed by various metals, occurs on the particle surface. The rate of de novo synthesis has been found to be much lower than the precursor synthesis.

Lighty and Veranth\(^{17}\) conclude that both mechanisms probably occur, but which formation pathway that dominates under practical combustion conditions is not known.

The dioxin emissions appear to be insensitive to the chlorine input\(^{17}\). In Sweden, the chlorine content in MSW varies between 1700 and 7900 g/ton fuel with an average of 5300 g/ton fuel. About 12 000 tons PVC is incinerated annually (it is estimated that about 27 700 tons PVC waste is put into landfills annually in Sweden) corresponding to about half of the chlorine content in waste assuming that the average chlorine content is 0.7%\(^{18}\).

At this chlorine content, other parameters such as boiler design and operating strategies are assumed to govern the dioxin emissions\(^{19,20,21}\). However, at higher chlorine content in the fuel mix there can be a coupling between the chlorine content and dibenzodioxin emission depending on the operating conditions. For a recent review of the literature regarding dibenzodioxin emissions for MSW incineration, the reader is referred to the work by Wikström\(^{19}\).

Brominated dibenzodioxins and furans (PBDD/PBDF)

From an environmental point of view, the possible formation and emission of brominated dibenzodioxins and furans is probably the most controversial issue regarding the waste incineration of material containing brominated flame-retardants.

In systems where both chlorine and bromine are present the distribution between brominated, chlorinated and mixed PXDD/PXDF will depend on the Cl:Br ratio but also the reactivity and stability of the compounds can be of importance. Due to the normal abundance of chlorine PCDD/PCDF dominate in waste incineration and only minor amounts of mixed bromochloro-dibenzodioxins or dibenzofurans are formed\(^{22}\). It should be noted that dibenzodioxins introduced to an incinerator with the waste are efficiently destroyed at the high temperatures prevailing during combustion.

Thus, as discussed above, other parameters than the chlorine loading normally governs the PCDD/PCDF emissions, and the total dioxin emissions are determined by operating conditions and the design of the incinerator and flue gas cleaning system. The effect of the bromine content will be to replace chlorine atoms in the PCDD/PCDF molecules.

It should also be noted that the apparent measured emissions of chlorinated dibenzodioxins/furans might decrease if bromine is included with the fuel. This is because dibenzodioxins/furans containing bromine are not measured and as a bromine atom replace a chlorine atom of a PCDD/F the molecule becomes “invisible” in the analysis.
**Heavy metals**

Heavy metals derive from the content in the fuel. Depending on the volatility (and chemical transformations) the heavy metals will split between the flue gas, fly ash and bottom slag. Emissions to the stack can occur as volatilised gas or as aerosol particles. The volatilisation can be preceded by the formation of chlorides that have a higher volatility and an increase of the chlorine feed promotes the transfer of heavy metals from the fuel bed. Similar effects can be expected for brominated flame retardants where antimony oxide is added to promote the flame retardancy. Indeed, antimony oxide is not volatile but it combines with halogens to form volatile compounds (antimony oxyhalide (SbOX) or antimony trihalide (SbX₃)), which facilitates the transport of the halogen and bromine from the condensed phase into the gas phase. The effect has been demonstrated in pilot-scale tests.

**Particulates**

Particulates consist of soot and ash particles. At high enough residence times and temperatures the soot particles will burn out. Volatilisation of volatile metals such as sodium, potassium, arsenic and cadmium followed by condensation as the flue gases are cooled, results in the formation of sub-micron aerosols. At higher combustion temperatures and at reducing conditions also otherwise stable components such as oxides of silica and calcium can be reduced and gasified. Sub-micron particles are detrimental to health due to their size but also since they act as carriers of toxic substances (such as Polycyclic aromatic compounds, PAC) that have been adsorbed on the particle surface. Also heavy metals are bound to the fine particulate matter.

The information above has been used to develop a strategy to estimate emissions to air from incineration. This strategy has been used in e.g. the TV case study. This strategy is given as an example below.

It is assumed that the incineration will take place in a dedicated waste incinerator equipped with an adequate flue gas cleaning system with maximum emissions in accordance with the proposed EU directive on waste incineration (Table A-2) or in accordance with recent Swedish statistics. The emissions are estimated for each individual waste component assuming stable combustion conditions.

Process derived emissions are simply calculated based on the fuel content of the component in question (for instance, all fuel carbon is assumed to be converted to CO₂). For emissions affected by the combustion process, the emissions are estimated based on literature data, annual emission statistics regarding total Swedish MSW incineration and the emission limits set by the proposed EU directive regarding incineration.

The basic assumptions include:

- **Boiler efficiency**: > 80 %
- **Flue gas flow**: 5 Nm³/kg waste (dry gas, 11 % O₂)
- **Heating value of waste**: 11 MJ/kg or 3 kWh/kg
- **Average chlorine content**: 5 000 mg/kg waste

**Carbon dioxide, CO₂**

For estimation of the CO₂ emissions it is assumed that all carbon is oxidised to CO₂. Thus, the small fractions of carbon contained in CO and hydrocarbons are for the purpose of calculating the CO₂ emissions neglected.
### Table A-2  Suggested air emission limits (11% O₂) in EU²⁵.

<table>
<thead>
<tr>
<th></th>
<th>Daily average values mg/m³</th>
<th>Half-hourly average values mg/m³</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>A (100%)</td>
</tr>
<tr>
<td>Total dust</td>
<td>10</td>
<td>30</td>
</tr>
<tr>
<td>Gaseous and vaporous substances⁶</td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td>HCl</td>
<td>10</td>
<td>60</td>
</tr>
<tr>
<td>HF</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>SO₂</td>
<td>50</td>
<td>200</td>
</tr>
<tr>
<td>CO</td>
<td>50⁷</td>
<td>100⁷</td>
</tr>
<tr>
<td>NOₓ as NO₂ᵇ (expressed as NO₂)</td>
<td>200</td>
<td>400</td>
</tr>
<tr>
<td>Heavy metalsᵈ</td>
<td>All average values over the sampling period of a minimum of 30 minutes and a maximum of 8 hours</td>
<td></td>
</tr>
<tr>
<td>Cadmium (Cd) and thallium (Tl)</td>
<td>total 0.05 mg/m³</td>
<td></td>
</tr>
<tr>
<td>Mercury (Hg)</td>
<td>0.05 mg/m³</td>
<td></td>
</tr>
<tr>
<td>Antimony (Sb), Arsenic (As), Lead (Pb), Chromium (Cr), Cobalt (Co), Copper (Cu), Manganese (Mn), Nickel (Ni), Vanadium (V), Tin (Sn)</td>
<td></td>
<td>total 0.5 mg/m³</td>
</tr>
<tr>
<td>Dioxins and furansᵉ</td>
<td>Average values for sampling period of minimum 6 hours and maximum 8 hours must not exceed 0.1 ng/m³</td>
<td></td>
</tr>
</tbody>
</table>

⁶Expressed as total organic carbon, TOC
⁷New incineration plants or plants with a capacity exceeding 6 tons/h
⁸Existing incineration plants with a capacity of 6 tons/h or less
ᵈThe metal and its compounds expressed as the metal
ᵉSee e.g. I-TEQ for equivalence factors.
⁷Excluding the start-up and shut-down phase. Exemptions may be authorised by the competent authority for incineration plants using fluidised bed technology, provided that the permit forsees an emission limit value of not more than 100 mg/nm³ as a hourly average value.
⁸At least 95% of all measurements.

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**Carbon monoxide, CO**

A small amount of the carbon will be emitted as CO. In 1997, the total emissions of CO in Sweden from MSW incineration was 807 ton which should be compared to 2.32 million ton CO₂ ²⁶ which means that approximately 350 mg CO is emitted for every kg of CO₂. At 11 % O₂ the emission limit for waste incineration will be 50 mg/Nm³ (Table A-2). 11 % O₂ or approximately 10 % CO₂ corresponds to approximately 196 g CO₂. Consequently, the EU-directive sets the CO emission to 260 mg CO for every kg of CO₂. In order not to underestimate the emissions, it is consequently assumed that 350 mg CO is emitted for every kg of CO₂ formed or 1280 mg/kg carbon in the waste.
Nitrogen oxides, NOx (NO and NO2)
The emissions of nitrogen oxides are the result of primary formation reactions (from the fuel nitrogen as well as from atmospheric nitrogen) and secondary reduction reactions (see the discussion above). A rough assumption is that all fuel nitrogen is primarily converted to NOx. The fuel nitrogen is the most important source for coal combustion contributing 70-80% of the total NOx emissions (from Kautsky and Royds27 quoted by Soud and Fukasawa28).

The total emissions in 1997 from MSW incineration in Sweden were 1 350 ton NOx calculated as NO2. With a total energy production of 5.1 TWh the NOx emissions correspond to 265 g NO2/MWh produced. With a boiler efficiency of 80%, the NO2 emission per kg input fuel would be about 330 g NO2/MWh waste input. The heating value of the waste mix in Sweden is about 12 MJ/kg (73% household waste, 11 MJ/kg, and 27% industrial waste, 15 MJ/kg). Using a conservative value of about 11 MJ/kg or 3 kWh/kg, it indicates an emission of 990 mg NO2/kg of waste at a boiler efficiency of 80%.

In household waste the nitrogen content varies but a mean value of 0.5% is assumed29. Converted to NO2 this yields about 16 400 mg NO2/kg of waste. Assuming an additional 10% thermal NOx yields about 18 000 mg NO2 primarily formed per kg of waste. The actual emissions are lower due to secondary destruction of NO and NO2 in substoichiometric zones as well as the employment of NOx reduction systems. Comparing the fuel nitrogen input with the actual emissions indicates a NOx reduction efficiency of about 95%. This high value reflects both efficient destruction, due to basic combustion mechanisms, and successful measures to further reduce the NOx formed. The result can be compared to the internal NO destruction in a CFBC, reported by Åmand, Leckner and Dam-Johansen9, who measured the NO concentration close to the air distributor to about 550 ppm whereas the concentration in the stack gases were about 50 ppm (a reduction of about 90%).

In accordance with the above discussion, the NOx emissions measured as NO2 is estimated to less than 163 mg/g N in the fuel (95% reduction). Thermal NOx emissions (10% of total NOx) are estimated from the heating value to 27 mg/kWh.

Note: 1 kg waste gives about 75 mg NO2/MJ which is slightly more than reported from the Swedish NOx fee system where the average is about 63 mg/MJ.

Nitrous oxide, N2O
The only source of any significance for N2O formation and emission in MSW incineration is the SNCR and/or SCR systems based on urea injection. Assuming that the NO reduction agent is ammonia, the N2O emissions are assumed to be insignificant.

Ammonia (NH3)
Assuming that the plant is equipped with a wet scrubbing system after the SNCR and/or SCR system the emissions of NH3 to the stack can be neglected.

Sulphur oxides, SOx (SO2 and SO3)
The sulphur oxide emissions can be calculated from the sulphur content in the fuel. The raw gas concentration would be 2 g SOx (calculated as SO2) per g sulphur introduced with the fuel. If the fuel contains species like calcium carbonate, some SO2 may be retained as calcium sulphate in the ash. At normal SO2 concentrations of 400 mg/Nm3 in the raw gas, the efficiency becomes ca 94% at emission levels of 25 mg/Nm3 (which is a normal target value in Sweden and correspond to half the proposed limit in the EU-directive). Assuming that all fuel sulphur is oxidised to SO2 (i.e. the retention in the ash is
neglected) and that the flue gas cleaning system removes 90% of the SO₂, the emissions can be estimated to 200 mg SO₂ per g sulphur introduced with the fuel.

*Hydrogen chloride, HCl, and chlorine, Cl₂*

Part of the chlorine will leave the incinerator with the ash streams and as particulate emissions. Also small amounts may be emitted as Cl₂. However, for reasons of simplicity it is assumed that all chlorine is converted to HCl, which is to a large extent removed in the scrubber system. The general emissions can be in the range of 10-30 mg/Nm³ (10% CO₂)³⁰.

The total emissions in Sweden in 1997 were 303 ton of HCl (about 295 ton Cl). Assuming a maximum of 0.8% of chlorine in the waste and a total waste incineration of 1.82 Mtonne the total chlorine throughput is 14 560 tonne. The total reduction efficiency is consequently about 98%. At a chlorine content of 0.4% the reduction efficiency would be 96%. As an average, it is assumed that 3% of the input chlorine is emitted to the recipient as HCl.

At a given reduction efficiency, the emissions will depend on the chlorine load. A reduction of 97% corresponds to emissions of about 30 mg/Nm³ at a chlorine load of 0.5% in the waste. Thus, it should be noted that adopting to the proposed EU Directive²⁵ (with a limit of 10 mg/Nm³ as daily average values and 60 mg/Nm³ as half-hourly average values) will lead to lower emissions.

Halogen compounds (Cl, Br, F) also take part in radical quenching reactions affecting the emissions of products of incomplete combustion (CO, VOC etc). However, these data are difficult to quantify and possible effects on the emissions are neglected.

*Hydrogen bromide, HBr, and bromine, Br₂*

The split between HBr and Br₂ is determined by thermodynamics as well as chemical kinetics. In comparison with the Cl₂:HCl ratio for chlorine the Br₂:HBr ratio will be larger and the emissions of Br₂ can possibly be significant under some conditions. As for chlorine, part of the bromine output will be in the form of ash and particulates. However, few data are available and as a first approximation it is assumed that all bromine is converted to HBr and that the removal efficiency of HBr is the same as for HCl. Consequently, it is assumed that 3% of the input bromine is emitted to the recipient as HBr.

Emission data for large-scale incinerators are missing in order to estimate the Br₂ emissions. However, laboratory investigations indicate that the conversion of bromine in a FR-containing plastic yields HBr. Benbow and Cullis³¹ found that the HBr concentration increases from zero at the polymer surface to a value corresponding to complete conversion at and beyond the flame front. These findings indicate that the maximum Br₂ emissions (HBr:Br₂ ratio) could be estimated from thermodynamics provided that the chemical kinetics does not control the conversion.

*Hydrogen fluoride, HF*

HF derives from combustion of fluorinated hydrocarbons such as PTFE. As for HCl and HBr, it is assumed that 3% of the fluorine input is emitted to the recipient as HF.

*Hydrocarbons*

In the literature, there are reports from biomass combustion plants showing that as the excess air is decreased (O₂ concentration decreases) the concentration of CO increases before the hydrocarbon concentration increases³². As a consequence, it can possibly be concluded that the hydrocarbon emissions can be neglected provided that the CO concentrations are maintained at a low level. An upper limit is given by the proposed EU-directive²⁵ corresponding to 10 mg organic carbon/Nm³. Since it is known that plastics
improve the combustion efficiency due to the high calorific content, co-combustion of plastics can result in lower emissions of hydrocarbons. With an average value of 5 Nm$^3$/kg waste, an upper limit for the emissions is assumed to be 50 mg organic carbon per kg waste.

**Polycyclic aromatic compounds, PAC**

The formation of soot passes over the formation of polycyclic aromatic compounds$^{33, 34, 35, 36}$ and the emissions of PAH can be correlated with soot. As it is a product of incomplete combustion it can also possibly be correlated with the emission of CO. Since it is known that plastics improve the combustion efficiency due to the high calorific content co-combustion of plastics can result in lower emissions of PAC. On the other hand, plastics containing halogens can result in higher emissions of products of incomplete combustion due to the interference of halogens with the radical chemistry.

Data from combustion of waste wood indicate$^{37}$ that the emissions are in the order of 2-5 µg/Nm$^3$ (Table A-3). The investigated plant was only equipped with an electrostatic filter and the emissions from modern MSW incinerators can be expected to be lower. Values of 0.1 µg/Nm$^3$ have for instance been reported$^1$.

However, in order not to underestimate the emissions, it is assumed that the emission of PAC (including PAH) is less than 1 µg/Nm$^3$, which corresponds to 5 µg/kg waste.

If the emissions of PAC prove to be important in the LCA model, the quality of the emission data should be improved.

### Table A-3  Combustion of waste wood$^{37}$.

<table>
<thead>
<tr>
<th></th>
<th>Waste wood (Sweden)</th>
<th>Waste wood (imported from Germany)</th>
<th>Forest residues</th>
</tr>
</thead>
<tbody>
<tr>
<td>PAH (µg/Nm$^3$)</td>
<td>2.5</td>
<td>4.9</td>
<td>5.2</td>
</tr>
<tr>
<td>Sum chlorobenzenes (µg/Nm$^3$)</td>
<td>6.9</td>
<td>2.5</td>
<td>0.3</td>
</tr>
<tr>
<td>Sum chlorophenols (µg/Nm$^3$)</td>
<td>3.1</td>
<td>1.5</td>
<td>-</td>
</tr>
<tr>
<td>TCDD-equiv., Eadon (ng/Nm$^3$)</td>
<td>-</td>
<td>0.30</td>
<td>0.02-0.05</td>
</tr>
<tr>
<td>TCDD-equiv., Nordic (ng/Nm$^3$)</td>
<td>-</td>
<td>0.24</td>
<td>-</td>
</tr>
</tbody>
</table>

**Halogenated dibenzodioxins and furans, PXDD/F**

Dibenzodioxins are a group of compounds and the characteristics of brominated dibenzodioxins/furans as well as mixed brominated and chlorinated dibenzodioxins/furans are not known in detail. Few data regarding PBDD/F emissions from commercial scale incineration plants have been published in the literature. Due to the similarities between the bromine and chlorine chemistry an assumption can be that PBDD/F forms at a similar rate as PCDD/F proportional to the ratio between Br and Cl in the waste. As both bromine and chlorine are present, the formation of mixed brominated and chlorinated dibenzodioxins and furans may be significant$^{38}$ with a distribution between brominated, chlorinated and mixed PXDD/F depending on the Cl:Br ratio.

In order to compare brominated dibenzodioxins/furans with the more studied chlorinated compounds and to estimate the emissions, the strategy described below was employed.
Chlorine and bromine are assumed to have identical characteristics, i.e. no difference is made regarding chemical characteristics, toxicity etc. PXDD/F with X being Cl, Br or both Cl and Br (i.e. three groups of compounds are formed; PCDD/F, PBDD/F and PBCDD/F) are then assumed to have the same toxicity as the corresponding chlorinated compounds and can be translated to TCDD equivalents. To differ between compounds containing chlorine and bromine, the brominated dibenzodioxins (including the mixed dibenzodioxins) are called TBDD/F.

As discussed above, several reports in the literature indicate that there is no coupling between input chlorine content and the resulting dioxin emissions at normal chlorine contents (below 10 000 mg/kg waste). Instead, the emissions are controlled by the combustor design and the flue gas cleaning system. It can also be noted that in the proposed EU-directive, hazardous wastes containing more than 1 % halogenated organic substances, expressed as chlorine, requires special combustion conditions. Thus, the maximum load of halogens in waste is assumed to be 1 % and the dioxin emissions (TCDD/F+TBDD/F) are assumed to be constant and set equal to the proposed EU-limit.

A small fraction, of the total halogen atoms, will be emitted in the form of TXDD/F. All halogen atoms are assumed to be converted to TXDD/F with the same efficiency, independent of the chemical form in which they are fed to the incinerator (for instance chlorine from PVC is assumed to perform as chlorine from NaCl).

A result of assuming a constant emission level is that the conversion efficiency of Cl/Br to TXDD/F will depend on the load of halogens in the waste. For instance, the following scenarios can be assumed:

- a low conversion efficiency (1 % Cl+Br in waste)
- a medium conversion efficiency (0.5 % Cl+Br in waste)
- a high conversion efficiency (0.1 % Cl+Br in waste)

The dioxin emission limit proposed in the waste directive\textsuperscript{25} is set to 0.1 ng TCDD eq./Nm\textsuperscript{3}. Assuming that the utilities will meet this requirement the maximum emissions can be estimated to this value at a normal chlorine content in the waste. Thus, assuming an average halogen content of 5000 mg/kg waste (medium scenario), a flue gas flow of 5 Nm\textsuperscript{3}/kg waste at 11 % O\textsubscript{2}, the dioxin emission is estimated to 0.50 ng TXDD equiv./kg waste or 0.10 ng TXDD equiv. per g halogen input.\textsuperscript{1} For the low and high conversion efficiency scenarios the corresponding figures become 0.05 and 0.5 ng TXDD equiv./g halogen input, respectively.

At normal chlorine and bromine concentrations the PBDD/F emissions would be much less than the PCDD/F emissions. At low concentrations, it is not unreasonable to assume that there would be a correlation between input Br and the formation of brominated dibenzodioxins and furans. Due to the limited amount of data it is difficult to draw definitive conclusions, but in a study in a commercial scale incinerator Lahl and co-workers\textsuperscript{39} found that the contents of brominated dibenzodioxins and furans increased with increasing Br load. Interestingly, they also found a strong increase in PCDD/F formation. This is in conflict with the TAMARA study\textsuperscript{2}, which indicated that the total formation of

\textsuperscript{1} It should be noted that today’s emissions may be higher. At the medium scenario level, the total Swedish annual dioxin emissions would correspond to 0.91 g dibenzodioxins complying with the EU directive. This should be compared with the annual emissions of 3 g in 1997. Consequently, the 1997 emissions are about three times higher and would correspond to maximum 1.65 ng TCDD equiv./kg waste.
halogenated dibenzodioxins/furans did not increase with the bromine input, although the distribution between various dibenzodioxins/furans changed.

For cases where the E&E waste is treated as a separate waste stream, it is reasonable to assume that incineration will take place in campaigns as batches are delivered to the incinerator. Assuming a mixing of 10 % waste from television sets and ordinary waste, and that the waste stream containing TV-housings has an average content of bromine of 2 %, the Br to Cl ratio would be about 2:5 g/g. At these bromine levels the formation of mixed dibenzodioxins are also important. As the brominated species increase, the chlorinated dibenzodioxins/furans will decrease since the emissions of TXDD/F are assumed to be constant. If the concentration of bromine is comparable with that of chlorine, it seems reasonable to assume that the TXDD/F emissions will be dominated by the mixed dibenzodioxins/furans. Thus, the emission of bromine containing compounds (TBDD/F) will be underestimated using the estimation above whereas the sum of TBDD/F and TCDD/F will be more correct. In order to estimate the split between brominated, chlorinated and mixed dibenzodioxins/furans more experimental data are required.

Metals
All metals that have an major effect on the environment and to the earth resources should be included in the model. The metals considered in this example are zinc, copper, aluminium, lead and antimony. The example is taken from the television study. Steel is also used in television sets and is treated as iron. The behaviour of metals in combustion depends to a large extent on the chemical form in which they exist. For instance zinc can occur as metal zinc, as zinc oxide, zinc chloride and zinc sulphate with very different characteristics as shown in Table A-4. Assuming that the metal enters the bed as ZnO it should be thermally stable and it appears safe to assume that the ZnO will leave the incinerator in the slag. However, the conditions in the bed are normally sub-stoichiometric with respect to oxygen and the ZnO may be reduced to Zn, which will devolatilise and be transported through the boiler with the combustion gases. Vaporised metals may then condense on heat exchanger surfaces or condense in the gas phase to form a fine particulate fraction in the sub-micron size that may cause fouling by impaction or be removed in the fly ash fraction. Consequently, the split between the grate ash/slag and the fly ash depends on boiler design, operating conditions (for instance local temperature and air stoichiometry) as well as the kinetic and thermodynamic characteristics of the metal compounds considered.

A rough estimate of the metal partition in a boiler can be obtained from the volatility numbers. Based on these numbers it is assumed that 50 % of the zinc, antimony and lead, 10 % of the copper and 1 % of the iron (steel) enters the freeboard and leaves the incinerator in the fly ash stream. The residual metals leave the system in the bottom ash/slag ash. Aluminium in its metal form will burn (31 MJ/kg) to form aluminium oxide (Al₂O₃), which is thermally stable (melting point 2045 °C and boiling point 2980 °C). Aluminium melts at 660 °C whereas the boiling point is 2467 °C. It is assumed that Al has a volatility similar to Cu, i.e. 10 % is assumed to be found in the fly ash stream.

<table>
<thead>
<tr>
<th>Table A-4 Physical characteristics for some zinc compounds</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Zn</td>
<td>ZnO</td>
<td>ZnCl₂</td>
<td>ZnSO₄</td>
</tr>
<tr>
<td>Melting point °C</td>
<td>420</td>
<td>1975</td>
<td>283</td>
</tr>
<tr>
<td>Boiling point °C</td>
<td>907</td>
<td>-</td>
<td>732</td>
</tr>
</tbody>
</table>
Particulates
Particulate emissions consist of soot and ash particles. At high enough residence times and temperatures the soot particles will burn out. Volatilisation of volatile metals such as sodium, potassium, arsenic and cadmium followed by condensation as the flue gases are cooled, results in the formation of sub-micron aerosols. At higher combustion temperatures and at reducing conditions also otherwise stable components such as oxides of silica and calcium can be reduced and gasified. Sub-micron particles are detrimental to health due to their size but also since they act as carriers of toxic substances (such as PAC) that have been adsorbed on the particle surface. Also heavy metals are bound to the fine particulate matter. For more details about particulate formation, see Smith\textsuperscript{41}. The fly ash content of products of incomplete combustion is generally low and fly ash can be assumed to derive from the ash forming minerals in the fuel.

As an upper limit, the EU-directive sets the maximum dust emissions to 10 mg/Nm\textsuperscript{3} and as for hydrocarbons (see above), the emissions are assumed to be less than 50 mg/kg waste or 200 mg/kg fuel ash input assuming a 25 \% ash content.

Landfill
In a Fire-LCA model the landfill alternative is one of the waste handling alternatives for an ordinary product life cycle. However, stricter regulations to minimise waste to landfills have been introduced in the European union as well as in the Nordic countries where even stricter regulations are in force. EU sets e.g. targets for the reduction of biodegradable wastes sent to landfill. In Sweden a ban on combustible waste to landfill was introduced in 2002 followed by a ban on organic waste to landfill 2005. Similar legislations are on its way in several other Nordic and European countries. This has influence both on the ordinary material flows (products without a fire) in the models but also concerning wastes from fires. Wastes from fires have normally been landfilled. This will be more difficult in the future in many countries. Incineration will in this case be an alternative.

One of the major problems connected with handling waste in LCA and system analyses is how to handle the time aspects in the landfill process. Most other processes in the life cycle of a product and most other waste treatment processes are “instantaneous”, and the emissions occur during a relatively short period. The emissions from e.g. transport are generated during the transport - and the total transport time is often in the magnitude of a day to a week. Waste that is put into a landfill, however, will generate emissions for several thousands years, see Figure A-1. The time aspects cause problems both when interpreting field data, and when comparing future emission with instantaneous emissions from other parts of the life cycle. To make the landfill emissions compatible to the emissions from the other stages of the LCA, we need a method to make a “capitalised value” of the future emissions.
Time aspects of landfilling in LCA are difficult to treat and have been discussed on numerous occasions. There is a consensus that the emissions should be integrated over a special period, and the integrated emission should be considered as occurring at the current moment. The different time approaches that have been proposed can be divided into:

1. Shorter time periods, either a specific fixed time period such as 15, 50, 100 or 500 years, or the so called responsibility time (which is usually 15 - 50 years), or a process time in the landfill (e.g. until some kind of pseudo-steady-state is obtained, see below).

2. Longer time periods, either a specific time (e.g. 1 million years), the period until the emissions reach a "background" level, or the infinite time period.

One difficulty is how to define the different time periods, and how to estimate the integrated emissions over each period. The definition of the time periods must be relevant with respect to the integration method and with the data used for integration.

In the approach developed at IVL both a short-term period and a long-term period are considered. The shorter time period is based on processes in the landfill. In several types of landfills there are consecutive processes. The first period is usually characterised by high internal activities, and the formation of emissions is to a large extent depending on parameters governed by the processes in the landfill. Later, the landfill will reach a kind of pseudo-steady-state and the formation of emissions is governed more by the external influence (percolation of water, diffusion of air oxygen, etc.).

We have called the short time period the surveyable time period. It is defined as the time period until the landfill reaches some kind of pseudo-steady-state. We have also suggested that the surveyable time period should be of the magnitude of one century. For a Municipal Solid Waste (MSW) landfill we have found that the surveyable time period corresponds to the time until the latter part of the methane phase (see below).

The longer time period is called the hypothetical, infinite time period, when all landfilled material has been released to the environment.

For both the surveyable time period and the hypothetical, infinite time period the emissions are assumed to occur at the current moment, i.e. \( t = 0 \).

The total, integrated emissions during the surveyable time period and the hypothetical infinite time period can be compared to the emissions from the other stages in the LCA.
The emissions during the surveyable period correspond to the emissions caused by the landfilled waste during the closest foreseeable future (i.e., in the magnitude of one century). The emissions during the hypothetical infinite time are also a “worst-case” scenario where all landfilled material has been released to the environment.

In the surveyable time period approach, the emissions are independent of site-specific data. The length of the surveyable time period may be different in, for example, the north of Sweden and the south of Italy, but the emissions during the surveyable time period will be equal for the same waste.

In our approach, information about the landfill processes is needed, but not about the kinetics of processes. Other approaches, when emissions are integrated over specific time periods, require knowledge of the chemical kinetics.

Our main approach for calculating the emissions from the surveyable time period and from the hypothetical, infinite time period is as follows:

1) The chemical, microbiological and physical processes in the landfill must be known. Information of the landfill processes can be obtained from a combination of mathematical models and experience from laboratory tests and from field data.

2) The composition of the waste, and relevant information about physical-chemical and biological properties of the waste must be known. Further, the composition and properties of the studied product must be known.

3) The emissions during both the surveyable time period and the infinite time period can be estimated from analyses of the waste (ultimate analysis, proximate analysis and analysis of species) with knowledge of the landfill chemistry.

In this application, Municipal Solid Waste (MSW) means the waste that is disposed at municipal waste facilities, mostly incineration plants and landfills. MSW is characterised as a mixture of several discarded products and materials: paper, plastic, wood, food and cooking wastes, garden wastes, glass, metals, ceramics, electronic scrap, etc. By legislation, many countries tries to minimise the total quantities of wastes e.g. by prohibit land-fill of organic materials.

MSW contains a large portion of organic degradable material. The degradation of this material governs the conditions in the landfill. When studying the whole landfill, the emissions from the landfill will have different characteristics, depending on which reactions dominate. Usually it is possible to identify several stages in the landfill behaviour. Understanding these stages is important for understanding the various emissions. The stages that can normally be identified are:

1. Initial stage: the period until the processes begin. The length of the initial stage may be from a week up to one year.
2. Oxygen and nitrate oxidation stage: the oxygen and nitrate in the landfilled waste are oxidising organic material. Since there is a limited amount of free oxygen and nitrate this stage is very short, often a few weeks. The main degradation products are water and carbon dioxide.
3. Acid anaerobic stage: characterised by a large formation of volatile fatty acids and acetic material. Some gas containing hydrogen and carbon dioxide is formed. The high content of fatty acids will decrease the pH, which can cause dissolution of metals that
will give high levels of metals in the leachate. The length of the period is from one year up to 10 years.

4. Methane stage: methane and carbon dioxide are formed, mainly from the fatty acids formed in the previous stage. Sulphur is transformed to sulphide that will bind metals. The pH is stable around neutral. The metal leakage is very low.

5. Humic stage: the relatively stable humic products are slowly degraded or mineralised. Ambient air oxygen will begin to diffuse into the landfill. Oxygen can also be transferred dissolved in the percolating rainwater. The oxygen inlet will cause an increase in the redox-potential, which can cause an oxidation of sulphides, and lead to an increased leakage of metals that have been bound as sulphides.

For the municipal solid waste landfill, it has been suggested that the surveyable period should correspond to the period until the later part of the methane stage, i.e., it should include the initial stage, the oxygen and nitrate reducing stage, the acid anaerobic stage and the larger part of the methane stage. These stages are characterised by a high internal activity, which is decreased at the end of the methane stage, when the external influence (e.g. oxygen diffusion) increases. At the end of the methane stage the landfill has reached a pseudo-steady-state.

After the methane stage, atmospheric oxygen can be transported into the landfill by rainwater or by diffusion. The oxygen can cause an oxidation of the sulphides, to which metals may be bound, which causes a release of metals to the leachate water.

The surveyable time period approach gives the following time schedule for emission of different components:
- the major parts of the emissions of metals are expected to occur after the surveyable time period, while
- the major part of the degradable organic material is emitted during the surveyable time period, and
- the more stable organic material (plastic, rubber, humus, etc.) will degrade very slowly, which causes emissions behind the surveyable time period. Stable organic compounds can be emitted in several different forms, i.e., pure leachage of original substances, as well as leachage of degraded compounds can occur. The degradation of the more stable materials can be both anaerobic and aerobic.

The hypothetical, infinite time period is defined as the time until the landfilled material is completely released to the environment, i.e., when all inorganic compounds in the landfill are released by leachate, by gases or by erosion. The organic compounds, largely humus, will be totally degraded to simple compounds and released by leachate, gas or erosion.

The emissions from MSW landfills are:
- Landfill gas: essentially methane gas, but different volatile constituents in the waste, as well as volatile degradation products may be present in the emitted gas.

- Leachate water: water polluted by both organic compounds and inorganic compounds, e.g. metals. It should be noted that the emissions in leachate can be both dissolved and in colloidal form.

Landfill gas
Landfill gas with a high methane concentration can be recovered from the landfill. The basic emission model is described in detail in the literature. The basic formation of potential emittants can be calculated from the chemical formula of the
organic material. However, not all of the reactants formed will be emitted. The landfill gas emissions can be reduced by recovery of the gas as a fuel.

The gross formation of methane is given in Table A-5. It is assumed that a part of the landfill gas is collected and recovered. It is assumed that approximately 50 % of the landfill gas formed is collected (if there is any collection system) and recovered as a fuel. The rest will migrate through the soil cover, where a part of the methane will be oxidised by microorganisms. At a typical landfill about 10 – 20 % will be oxidised.

**Carbon mass balance**

Mass-balances from field studies indicate that approximately 1 mass-% of the degraded carbon will outflow via leachate, mainly as fatty acids, and 99 mass-% via the landfill gas as CH4 and CO2.

The landfill formed gas contains mainly CH4 and CO2. Different organic materials give different ratios between CH4 and CO2. Part of the gas can be recovered as fuel gas. The collection yields have often been very low. Collection efficiencies between 10 and 50 % have been reported. The non-recovered gas will migrate through the soil cover, and methane-oxidising microorganisms in the soil will oxidise a part (10 – 20 %) of the methane to carbon dioxide.

**Table A-5  Methane formation (during surveyable time period) and concentrations in landfill gas. All figures are related to dry, organic (ash free) substance**

<table>
<thead>
<tr>
<th>Compound</th>
<th>Degradation ratio during surveyable time period</th>
<th>Methane ratio in gas</th>
<th>Quantity of formed methane during surveyable time period</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>kg degraded C per kg C in material</td>
<td>CH4/( CH4+CO2)</td>
<td>kg CH4 per kg material</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>kmol/kmol or Nm³/Nm³</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Protein</td>
<td>100%</td>
<td>0.52</td>
<td>0.361</td>
<td></td>
</tr>
<tr>
<td>Fat</td>
<td>100%</td>
<td>0.82</td>
<td>0.75</td>
<td></td>
</tr>
<tr>
<td>Cellulose and hemicellulose</td>
<td>70%</td>
<td>0.50</td>
<td>0.227</td>
<td></td>
</tr>
<tr>
<td>Degradable carbohydrates, starch, sugar</td>
<td>100%</td>
<td>0.50</td>
<td>0.324</td>
<td></td>
</tr>
<tr>
<td>Humus, lignin, etc.</td>
<td>0%</td>
<td>0.49</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Polyethylene, PE</td>
<td>3%</td>
<td>0.75</td>
<td>0.026</td>
<td></td>
</tr>
<tr>
<td>Polystyrene, PS</td>
<td>3%</td>
<td>0.62</td>
<td>0.023</td>
<td>Also ~0.02 kg styrene in gas</td>
</tr>
<tr>
<td>Polyethylene terephthalate, PET</td>
<td>2%</td>
<td>0.50</td>
<td>0.0076</td>
<td></td>
</tr>
<tr>
<td>Poly vinyl chloride, PVC</td>
<td>3%</td>
<td>0.69</td>
<td>0.024</td>
<td>0.0175 kg HCl, and some vinyl chloride monomer in gas and leachate</td>
</tr>
</tbody>
</table>

**Nitrogen and sulphur balance**

It is assumed that all nitrogen in the degraded organic material is transformed into ammonia or ammonium. The major part of the ammonia formed will be transferred to the leachate and emitted as NH3/NH4+ in the leachate water.
Similarly, it is assumed that all sulphur in the degraded organic material is transformed to hydrogen sulphide or metal sulphides. The hydrogen sulphide and metal sulphides will, to a large extend, be precipitated as solid metal sulphides and retained in the solid phase, thus immobilising these metals.

**Metal emissions**
Metals in the waste will be dissolved by the percolating water and thus transferred to the leachate water. Several mechanisms, e.g. sulphide precipitation, will decrease the metal emission. The metal emission level can be relatively high during the acid anaerobic stage, but very low during the methane stage. Mercury is also assumed to evaporate into the ambient air from the landfill.

Metals in municipal solid waste can be divided into metallic materials and metal compounds. The latter may, for example, be present as additives in different materials. Before metals can be emitted via leachate they must be released from the solid waste matrix into the percolating water. In the case of metallic materials, the release process is corrosion. In case of additives the release can be governed by the decomposition of the solid matrix or by diffusion into and out of the solid matrix. Once released to the water, the metals may be precipitated or sorbed to the solid phase. Once released and dissolved in the leachate, however, the fate of the metal is independent of its origin.

**Emissions of specific organic compounds**
Organic compounds are used in several products that occur in the waste. Some compounds are used as solvents. Other compounds are used as additives, e.g. in plastic, rubber or paper. These compounds may give rise to emissions in the leachate or in the landfill gas. Organic compounds are also formed during the degradation of organic material, especially volatile fatty acids and alcohols, ketones and aldehydes. Emissions of specific organic compounds from landfills are relatively poorly analysed.

The actual emissions of organic compounds from landfills depend on the fate of the compounds inside the landfill, due to processes that are specific for each compound. A conceptual model, that predicts the emission of organic compounds from landfills, has been developed by Öman. This model has been verified in a pilot study. The conceptual model is shown in Figure A-2. In the model the residence times of specific organic compounds inside landfills are primarily dependent on the sorption of the compounds to solid material and on the water transport. The residence times are then crucial for whether compounds will be transformed or evaporated during this time.
Landfill fires occur frequently on most landfills. It has previously been pointed out that, emissions of PAH, dibenzodioxins, and other emittants from landfill fires can be of large importance\textsuperscript{43,44}. Due to lack of information, however, these emissions have not been included explicitly.
Recycling

The recycling processes are strongly related to the specific materials involved in the particular model. A normal LCA procedure for handling of the process can thus be used. The resolution of the process is however also here an important issue. The introduction of a flame retardant can have a major effect on the possibility to recycling a material. Special sorting or classification procedures may be needed to prevent contamination of other recycled materials with flame-retardants. Those effects have to be covered by the LCA model.
References


21 Wikström, E. and Marklund, S., ”The influence of level and chlorine source on the formation of mono- to octa-CDDs/Fss and coplanar PCBs during MSW combustion”, Chemosphere, submitted 1999.


Appendix B: Application examples

Three different case studies using the Fire-LCA method have been conducted, i.e. TV\(^1\), cable\(^2\) and furniture\(^3\) case study. The definition of the statistical fire model is discussed below for each of the three cases. In addition the experimental set-up and the fire emission data used as input to the fire-LCA model in each of the three cases, is discussed.

TV set case study

In the TV case study\(^1\) a TV complying with the European regulations was compared to a TV complying with the regulations in US. The US TV contained high fire performance material (UL94 V0) in the outer enclosure while the European TV contained material that was easy to ignite and spread a fire readily (UL94 HB) in its outer enclosure. The high performance material was flame retarded HIPS (using deca-BDE) while the low fire performance material was untreated HIPS.

Statistical fire model

The statistical fire model was set up using a compilation of statistics from Europe by Sambrook\(^4\) and a specific detailed study from Sweden"Vällingby"\(^5\) together with statistics from the NFPA in the US.

The criteria under which fires are counted as TV set fires varies significantly from one country or from one statistics collecting organisation to another. The Sambrook study defines a TV set fire as follows: “A TV fire is a fire where the first point of ignition is from within the structure of the TV or ancillary equipment that forms a part of the TV, [such as] a video recorder or satellite system. [...] The resultant fire will have breached the envelope of the TV [...]. Specifically excluded are acts of vandalism, criminal damage, ignition caused by the use of accelerants and electrocution as a result of tampering.” This is in accordance with the safety standards as defined by IEC 60065 and is the definition used by National Electrical Safety Boards throughout Europe. This definition tends to narrow statistics to fires of electrical origin, excluding most other causes. Significantly, fires that are contained within a TV set’s enclosure are ignored, highlighting the important role enclosures play by providing the last barrier to any internal fire spreading outside the TV set. In addition, this definition excludes external causes such as candles.

Fire brigades and insurance companies, on the other hand, tend to report higher figures due to a broader definition of TV set fires that includes fires initiated externally. Insurance companies are generally more inclusive than other organisations in their definition of a TV fire. A detailed investigation of Insurance Company statistics in Sweden\(^2\) found that approximately 50% of all TV fires as defined by insurance companies in Sweden would not qualify as TV fires according to the Sambrook definition. The discrepancy arises from the fact that fires confined only to within a TV set enclosure are included in the insurance company figures. Significantly, the Sambrook study has concluded that the occurrence of fires throughout Europe seems to be essentially the same (normalised per million TV sets) in each individual country. The Sambrook study relies on statistics from similar sources in each country. Assuming that the Sambrook conclusion is correct in indicating this similarity in fire behaviour the Swedish data was used as a model for Europe.

At the time of the study by Sambrook the Swedish data were not available. Therefore, Sambrook has accounted for the inclusion of ‘fires’ due to external ignition sources, or
due to incorrect classification of the type described above, by estimating these effects in each country studied. The conclusions of the Sambrook survey suggest that about two thirds of the total number of TV set fires reported are due to internal/electrical causes and about one third to external causes. Based on their purposely-conservative definition of TV set fires, Sambrook concludes that there are approximately 2208 fires in Europe per year, or 12.2 TV fires per million TV sets. They further conclude that another 6 TV fires per million TV sets are caused by external ignition.

Sweden is the first European country to make a concerted effort to reconcile the differences between fires statistics for TV fires from different sources. In order to determine which number was most realistic an in-depth study was initiated centred around the Stockholm suburb of Vällingby. Over a 14 month period all electrical fires were investigated in detail by experts from SEMKO. The results of their findings were extrapolated to cover the whole of Sweden.

Two findings were particularly interesting. First, the Insurance federation grossly over-estimated the total number of electrical fires and in particular the number of TV fires, and second, SEMKO had previously underestimated the total number of TV fires. Using SEMKO’s definition, the Vällingby study estimated that approximately 750 (or between 600-900) audio/visual fires occur per year in Sweden. These fires were all large enough to have breached the TV enclosure SEMKO concluded that the additional 1750 fires reported by the Insurance Federation were either wrongly classified, e.g., so small that they had not breached the enclosure, or were caused by an external ignition source. Assuming that approximately half of the Insurance Federation fires did not breach the housing would leave approximately 500 due to external ignition sources. These data correspond to approximately 100 TV fires/million TVs in Sweden due to internal ignition and 65 TV fires/million TVs due to external ignition, and 160 TV fires/million TVs where the fire does not breach the enclosure.

Usually, only the most severe TV set fires find their way into electrical safety board or fire brigade statistics. It was decided in the TV case study1 that the Vällingby project results, because of the thoroughness of the methodology, were more representative of a wider European reality.

In conclusion, the Sambrook study provides a sound basis for comparison of fire statistics from different European countries, but it is too conservative in its estimate of the frequency of TV fires. The Vällingby data provided a better model for European TV set fire behaviour.

The results showed that a figure of approximately 100 TVs/million burn in Europe each year due to internal ignition sources and a further 65 TVs/million due to external sources. The distribution according to size of the fire is based on German results. It was assumed that European TVs do not contain any flame-retardants.

A further 160 TVs/million classified as being involved in fires by insurance companies were assumed to be restricted to inside the TVs and correspond to the category of ‘minor’ primary fires in the LCA model. This means that the model proposed as a part of the Preparatory Study for Europe was changed slightly.
### Table B-1  Severity of TV set fires in Germany.

<table>
<thead>
<tr>
<th>Severity</th>
<th>Frequency (%)</th>
<th>% used in model</th>
<th># used in LCA model</th>
<th>Category in LCA model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fire restricted to the TV</td>
<td>30-40</td>
<td>35</td>
<td>58</td>
<td>minor</td>
</tr>
<tr>
<td>Fire spread beyond the TV and causing damage to the property</td>
<td>40-60</td>
<td>53</td>
<td>88</td>
<td>full TV</td>
</tr>
<tr>
<td>Fire causing severe damage to the room and property</td>
<td>&lt;5</td>
<td>5</td>
<td>8</td>
<td>full room</td>
</tr>
<tr>
<td>Fire causing major damage to the entire dwelling</td>
<td>&lt;5</td>
<td>5</td>
<td>8</td>
<td>full house</td>
</tr>
<tr>
<td>Fire completely destroying the building</td>
<td>&lt;2</td>
<td>2</td>
<td>3</td>
<td>full house</td>
</tr>
</tbody>
</table>

### Fire experiments and LCA input data

It was deemed reasonable to assume that any external ignition of TVs in the US must either pertain to a large external ignition source, or be due to the presence of a small but significant number of TV sets with HB enclosure material. This assumption was based on the experiments conducted in the study. Thus, assuming that the distribution between internal and external ignition in the US TV fires is the same as for the Swedish TVs one can determine that approximately 8 TVs/million are ignited internally and the remaining 5 TVs/million are ignited externally. In this model we have defined the internal fires as not going beyond the enclosure while by definition the external fires go beyond the enclosure. Thus, only the 5 TV fires/million TV sets are included in the US based model of the V0 TV performance. Based on experimental evidence of the fire behaviour of V0 enclosure material one can assume that these fires are essentially minor with little damage to material other than the TV of origin and thus it was assumed that these fires gave no emissions.

### Table B-2  Emissions from fires associated with burning of TVs with NFR enclosures in one year.

<table>
<thead>
<tr>
<th>Type of fires</th>
<th>Size</th>
<th>Fire Emissions</th>
<th>Other Emissions</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Primary Fires</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>107</td>
<td>88 × full TV</td>
<td>88 × FE(TV1-B)</td>
<td>88 × RE(TV1-P)</td>
</tr>
<tr>
<td></td>
<td>8 × full room</td>
<td>8 × FE(TV1-Room)</td>
<td>8 × RE(Room-P)</td>
</tr>
<tr>
<td></td>
<td>11 × full house</td>
<td>11 × FE(TV1-House)</td>
<td>11 × RE(House-P)</td>
</tr>
<tr>
<td>218&quot; - minor</td>
<td>30% replacement</td>
<td>0</td>
<td>0,3 × 218 × RE(TV1-P)</td>
</tr>
<tr>
<td><strong>Secondary Fires</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 - house fires</td>
<td>6 × full TV</td>
<td>6 × FE(TV1-B)</td>
<td>6 × RE(TV1-P)</td>
</tr>
</tbody>
</table>

*This number corresponds to 160 minor fires from Insurance Federation statistics plus 58 minor fires using the German division of the fire statistics.*
Table B-3  Emissions from fires associated with burning FR TVs in one year.

<table>
<thead>
<tr>
<th>Type of fires</th>
<th>Size</th>
<th>Fire Emissions</th>
<th>Other Emissions</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Primary Fires</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 - ‘internal’</td>
<td>$5 \times \text{minor fire}$</td>
<td>0.</td>
<td>$5 \times \text{RE(TV2-P)}$</td>
</tr>
<tr>
<td>160 - minor</td>
<td>$30% \text{replacement}$</td>
<td>0.</td>
<td>$0.3 \times 160 \times \text{RE(TV2-P)}$</td>
</tr>
<tr>
<td><strong>Secondary Fires</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 - house fires</td>
<td>$6 \times \text{full TV}$</td>
<td>$6 \times \text{FE(TV2-B)}$</td>
<td>$6 \times \text{RE(TV1-P)}$</td>
</tr>
</tbody>
</table>

Certain input was required for the LCA model. These are defined below:

- $\text{FE(TV1-B)} = \text{Fire Emissions associated with burning of a TV without FR in enclosure}$
- $\text{FE(TV1-Room)} = \text{Fire Emissions associated with burning of full room due to ignition of a TV without FR in enclosure}$
- $\text{FE(TV1-House)} = \text{Fire Emissions associated with burning of a full house due to ignition of a TV without FR in enclosure}$
- $\text{RE(TV1-P)} = \text{Replacement Emissions associated with a TV without FR in enclosure}$
- $\text{RE(Room-P)} = \text{Replacement Emissions associated with a full room containing a TV without FR in enclosure}$
- $\text{FE(TV2-B)} = \text{Fire Emissions associated with burning of a TV with FR in enclosure, burning as part of a house fire, and}$
- $\text{RE(TV2-P)} = \text{Replacement Emissions associated with a TV with FR in enclosure}$

In order to apply this information the LCA model requires emission data from a burning TV with NFR enclosure material, a burning TV with FR enclosure material, a burning room where the TV with NFR enclosure material is the ignition source and a similar room containing an TV with FR enclosure material where something other than the TV is the ignition source. Finally information is required concerning emission from a burning house.

In the case of the burning TV containing FR in the enclosure the fire experiments indicated that this type of TV is very difficult to ignite and it is assumed that the fire emissions are minimal for the 5 FR TVs that burn per millions TVs in the US. Thus in the LCA model $\text{FE(TV2-B)} = 0$ in the case of primary fires.

Full room experiments provided input to the TV-room and TV-dwelling parts of the model. Experiment 1 was designed to model a scenario there the TV is the ignition source with the fire spreading to engulf the entire room. A Swedish TV was used in this experiment. The ignition source was a candle placed beside the TV.

Experiment 2 was designed to model a scenario where the US TV was involved in a fire but not the ignition source. The ignition source was a candle placed in the sofa. An attempt was made first to light the US TV using this ignition source without success.

Experiment 3 was designed to model a scenario where the Swedish TV was involved in a fire but not the ignition source. As in the case of experiment 2, the ignition source was a candle placed in the sofa.

In the case of experiment 1 the emission data was reduced to emissions per $m^2$ as input to the LCA model and used both as room emission data and full house emission data. The
scale up was done on an area basis using an area of 16 m² for a typical room and 121 m² as a typical house.

In the case of experiments 2 and 3 only the fire emissions from the TVs are included explicitly in the model. The pattern of emissions from these 2 experiments is similar due mainly to the fact that the fire development is essentially equivalent. These results indicate that emission of species from secondary TV fires is independent of the presence or absence of the flame retardant in the TV. Thus, the emissions from the free burning Swedish TV fire are used in both cases. This is the best approximation we have available at the moment and is probably a worst case set of emissions as the free burn experiment was by no means as hot as a flashed-over room.

**Cable case study**

The cables study compared two indoor electrical cables with essentially the same fire performance. In both cases the material could be easily ignited and spread a flame readily in the IEC 60332-3 test (a large scale test of cable fire performance). Thus the same fire model was used for both cables and the LCA became essentially a comparison of different material choices. The two cables chosen in the comparison were a flexible PVC cable and a flame retarded polyolefin cable.

**Statistical fire model**

Using fire statistics collected from countries in Europe, it was estimated that a total amount of 35 fires occur per million dwellings due to cables. Based on data from Denmark, each dwelling was estimated to contain (on average) 250 m of cable, and it was assumed that approximately 50 m of cables are present on average in a single room. This corresponds to 140 fires per million km of cables that can be assumed to be caused by electrical wiring and cables, i.e. so called primary fires.

Using statistics mainly from the UK Home Office and from SRV Sweden concerning distribution of the size of the fire (the fire spread), the number of fires that are confined to the cable only (“Cables Fire”), spread beyond the cable but contained in the room of origin (“Cable/Room” fires) and those that cause significant damage to the dwelling (“Cable/House” fires) can be estimated. The results of this division are summarised in Table B-4.

No information could be found about how important the choice of cable material (e.g. PVC or PE) is regarding the frequency of electrical fires. No information could be found where the amounts of fires caused by cables were, or could be, distributed based on the specific material used in the cables causing the electric fires. Thus, it was assumed that there is no difference between the fire models that are used in the two cable LCA models.

Using the result of these calculations together with information regarding the total amount of cables in a typical dwelling it is possible to estimate the length of cables burned in primary fires each year, and thus the amounts of cables burned in 30 years, which is the estimated lifetime of the cables used in the LCA model. The final result of these calculations are values (in percent), which describes the amount of cables, which are destroyed in primary fires, of the total amount of cables used in the LCA model. These values are used as input in the model, see Figure B-1.
Table B-4  Calculation procedure of fire statistics.

<table>
<thead>
<tr>
<th>Type of fire</th>
<th>Fire spread (%)</th>
<th>Fires (nr.)</th>
<th>Cable length burned/year (m)</th>
<th>Cable length burned in 30 years (km)</th>
<th>% of $10^6$ km cables</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cables fire</td>
<td>60</td>
<td>84</td>
<td>2100</td>
<td>63</td>
<td>0,0063</td>
</tr>
<tr>
<td>Cable/Room fire</td>
<td>31</td>
<td>43</td>
<td>2150</td>
<td>64,5</td>
<td>0,00645</td>
</tr>
<tr>
<td>Cable/House fire</td>
<td>9</td>
<td>13</td>
<td>3250</td>
<td>97,5</td>
<td>0,00975</td>
</tr>
</tbody>
</table>

Further, it is assumed that 50 % of all the cables in the room in the “Cables only” category are involved in the fire.

It is estimated that all “Cable fires” are vitiated, i.e. emissions data for this module are based on the results from the vitiated cable experiments. When a cable fire starts, the atmosphere in the vicinity of the fire may be well ventilated, but as the fire develops and progresses, the atmosphere becomes vitiated. Due to this behaviour, all fires used in the LCA model are estimated to be vitiated fires, but as a complement a module describing well-ventilated “Cable fires” is included in the model. An investigation of the impact of using the results of the "well ventilated" experimental data into this module instead of the vitiated data indicates that the impact is small using the experimental emissions we had available.

As seen in Table B-4, the amounts of cables destroyed in primary fires, as a part of the total amount of cables used in the model, are very small. This is a reflection of the fact that very little statistical evidence is available that fires begin in cables and electrical wiring.

Based again on UK Home Office statistics and statistics from SRV Sweden it was estimated that approximately 1400 serious fires occur annually per million dwellings$^{12}$. 
Serious fires are fires where the dwelling is severely damaged, or totally destroyed, by the fire. It is assumed that there is approximately 250 m cable per dwelling. By using this number and the estimated amount of serious fires occurring annually per million dwellings, the corresponding amount of serious fires per million km of cables is 5600.

The total length of cables that is destroyed each year in serious fires is 1400 km, if it is assumed that 100% of the cables present in the dwellings are destroyed. This amount of cables is used in the model as a “worst case scenario”, where all cables in the dwellings are assumed to be destroyed. If the estimated life time of the cables is 30 years, 42000 km of cables is destroyed in serious fires during the life cycle of the cable, or 4.2% of the total amount of cables that is used in the LCA model.

In addition was the sensitivity of the results to the number of secondary fires investigated by including a scenario where it was assumed that only 10% (instead of 100%) of the amount of cables used in the dwellings that are exposed to serious fires are actually destroyed in the fire. If 10% of all the cables in each dwelling are destroyed, this corresponds to 140 km of cables that are destroyed in fires each year. This has been used as a “realistic estimate” of the contribution of secondary fires.

**Fire experiments and LCA input data**

Large scale experiments were performed according to a modified version of the IEC 332-3 standard. The combustion chamber was as specified in IEC 332-3. A schematic of the experimental set-up is shown in Figure B-2. Gas analyses were performed in the exhaust duct placed above the chamber. The Heat Release Rate (HRR) was measured together with CO and CO₂ as in most fire tests. In addition FTIR measurements similar to those conducted in the small scale experiments were performed, together with chemical analysis of PAHs, dibenzodioxins, furans and Volatile Organic Compounds (VOC). The exhaust duct is 40 cm in diameter. The chemical analysis and FTIR measurements were made 2.5 m after any guide vanes or bends of the duct. The HRR, CO and CO₂ measurements were made 3.5 m after the guide vanes and bends.

The chamber where the cables are mounted is often referred to as "the kiosk" since it looks like an old telephone kiosk. The kiosk is 1000 × 2000 × 4000 mm³. It has a door opening large enough to facilitate easy mounting of the cable tray. There is an air inlet in the bottom of the kiosk, which is connected to a fan, which supplies an airflow of 6500 l/min. There is a glass window in the door to facilitate video recording and estimating flame spread during IEC 332-3 test. The ignition burner used was a 20 kW propane.

Two tests were performed for each cable, one well ventilated and one vitiated. In addition one blank test with a propane burner of 120 kW for 10 minutes was performed. In all cable tests, the weight of the cable tray before and after the test was registered to facilitate the calculation of yields. In addition material that had fallen onto the floor was collected and weighed. In all tests 15 cables 2.7 m long were mounted on the cable tray with one cable diameter between each cable.
In the well-ventilated experiments, an airflow of 6500 l/min was supplied into the apparatus. However, the air available in the kiosk is substantial, and therefore in order to create a somewhat vitiated atmosphere in the vitiated experiments the airflow was switched off and a 100 kW burner was used for two and a half minute before igniting the cables. The extra burner consumed about $100 / \left(12.8 \times 2.5 \times 60\right)$ g oxygen which means that the oxygen concentration in the chamber when the cables was ignited was in excess of 10 %.

The quantification of the detected products has been conducted from the time when the burner, that ignited the cables, was started, until the end of the test. The burners used in the experiments are very efficient and produce mainly CO$_2$ from the combustion of carbon. The amount of CO$_2$ produced from the burners was subtracted from the amount of CO$_2$ detected by the FTIR. Thus, the amount of CO$_2$ presented in the tables represents the amounts of CO$_2$ produced by the decomposition process of the cables being studied.

It is estimated that the CO$_2$ produced by the first burner (used to lower the concentration of O$_2$) disappears quite fast in the ventilation duct. However, in the beginning of the quantification, there are still remains that might make the concentration of CO$_2$ a little bit too high (approximately 0.1%). A rough calculation indicates that the remaining CO$_2$ may enhance the total mass produced of CO$_2$ with about 1-2 %.

As described previously the Cables Fire-LCA model defined was endeavoured to compare two products with equivalent fire behaviour. In this context, the end-of-life (EOL) scenarios were deemed to be very important to the outcome of the model. At present the
The majority of cable waste is either left in building (i.e., disconnected but not removed) or sent to Landfill in lieu of a better alternative. A number of future alternatives were, however, identified as important to investigate. The four EOL scenarios that were selected for detailed study were:

- Scenario 1: 100% landfill plastics and copper
- Scenario 2: 100% landfill plastics, 100% material recycling copper
- Scenario 3: 100% energy recovery plastics, 100% material recycling copper
- Scenario 4: 100% material recycling plastics, 100% material recycling copper

These scenarios were selected to focus on extreme situations. In real life one would expect a percentage of material to go to recycling in some form, which would be less than 100% but more than 0%.

Effort was expended to obtain information concerning well-ventilated and vitiated combustion products from the large-scale experiments for use in different parts of the LCA model. In the cases where the cables are involved in a larger fire (i.e., all secondary fires, all “Cable-room” fires and all “Cable-house” fires) the vitiated information was used. In the case where the cables were involved in fires that did not spread beyond the object of origin then the opportunity to use well-ventilated cable fire information was available. A comparison was made between the results for scenario 1 depending on whether vitiated data is used throughout or well-ventilated data has been used for the “Cables only” category in the Fire-LCA model. This comparison yielded very little difference and based on this comparison the vitiated emission results were used for all cable fires.

For the room and house emissions, data from experiment 1 in the TV study, i.e. a room with a non FR-retarded TV was used together with the dioxin emissions from the vitiated experiments in the kiosk.

**Furniture case study**

The furniture case study compared two different high fire performance UK sofas with a low fire performance mainland European sofa. The high fire performance sofas contained a phosphorous-based flame retardant in the foam and two different flame-retardants in the material used on the sofa decorative cover. The mainland European sofa did not contain flame retardant treated material or foam.

**Statistical fire model**

In 1988 the UK Government introduced the Furniture and Furnishing (Fire) (Safety) Regulations 1988. This required the cigarette and match equivalent resistance tests for a furniture fabric and a mass lost test for fillings.

The statistics presently available in the UK are based on a sofa population that consists of both pre-1988 and post-1988 furniture. To define the effect of the presence of ignition resistant sofas in the 1999 statistics two scenarios was considered. In the first case the model assumes that a sofa has a lifetime that is exponentially distributed with the expectation value of 10 years that results in a population with 63% of the sofas containing combustion modified materials in 1999. In the second case a mean lifetime of 15 years has been assumed which results in a population with 49% of the sofas containing combustion-modified material in 1999. In addition it is assumed that each household has 2 sofas and the sofas are placed in the living room.
The fire model was constructed from studying fire and population statistics in UK. The UK had 23.9 million households in spring 2000 and 22.4 million households in 1999. There were 70 300 dwelling fires in 1999 and 64 500 in 1989. According to the DTLR statistics 5500 fires per year spread beyond the room of origin but are confined to the building on average, in the late 90's. Since 1989 there is an increasing trend for "confined to item" and a decreasing trend for "confined to room". In 1989, 32 500 fires were confined to room (50 %) and 26 300 to item (41 %). In 1999, 29 200 fires were confined to room (41 %) and 34 800 to item (50 %). During this time period there has been a change in the way fires are reported, which makes it more difficult to interpret the data. This change in reporting data is to some extent taken into account by not including the fires reported as "No fire damage" when calculating the percentages. Assuming that the change in confined to item and room depends solely on the increasing number of FR treated sofas results in a model where, if all sofas were FR, 36 % of the fires would be confined to room and 55 % confined to item. Assuming that the change in confined to item depends solely on the change in the Fire Regulations is probably not correct but provides a starting point for the model. Another extreme is to assume that the change in confined to item depends only on other factors such as smoke detectors, less smoking etc which is probably also incorrect.

In 1999 around 10 fires started in combustion modified upholstery and 500 in other upholstery. The number of fires per year is then calculated using:

\[
\# \text{fires}_{\text{sofaA}} / \text{year} = \frac{\# \text{fires}_{\text{sofaA}}}{\chi_{\text{sofaA}} \cdot X \cdot B}
\]

where \#\text{fires}_{\text{sofaA}}/\text{year} is the total number of fires in a particular type of sofa (i.e. combustion modified or otherwise) each year, \(\chi_{\text{sofaA}}\) is the percentage of fires in this type of sofa each year, \(X\) is the number of sofas per household (i.e. 2) and \(B\) is the total number of households (assumed to be 23,9 million in 1999).

Assuming that all 10 fires started in combustion-modified upholstery are fires in sofas result in 0.33 fires per million FR sofas and 28.3 fires per million non-FR treated sofas. The DTI studies indicate that the number of fires in FR furniture may actually be higher. This is, however, based on an extrapolation of the data post 1988 that has not been included in this model.

According to statistics from Surrey the number of fires starting in the living room in UK was rather constant until 1986 ( = 0.5 fires/1000 households) when the number suddenly decreased to 0.45 fires/1000 households in 1987 and has continued to decrease slightly since then. In 1999 the number of fires starting in the living room in UK was 8 600. Subtracting the number of fires starting in sofas, i.e. 500 + 10, results in 8090 fires. Out of these 41 % are confined to the room but beyond starting item assuming that confined to room is independent of starting room, i.e. 3 317 fires which is equivalent to 69 fires/million sofas. The 5500 fires that are confined to building results in 115 fires per million sofas.

The results for the LCA model for UK and mainland European fires in sofas, assuming that “confined to item/room” is independent of room and starting item, are summarised in Table B-5.

\[\text{i} \ 10/(0.63*2*23.9)\]
\[\text{ii} \ 500/(0.37*2*23.9)\]
The number of sofas that are replaced when the fire is too small to be reported to the fire brigade is not available in the DTLR statistics. Swedish\textsuperscript{22, 23} and UK statistics\textsuperscript{24} indicate that about 13% of all fires are reported in the fire statistics. Assuming that the same figure applies to fires in sofas gives that \((0.33/0.13-0.33=)\ 2.2\) fires occur in the UK and \((28/0.13-28=)\ 187\) fires occur in the EU per million sofas each year that are not reported to the fire brigade. In this model it has been assumed that the same number of sofas are ignited independent of the presence of flame retardants but that a more limited number increase to a fire that is reported to the fire brigade in the UK. This results in \((28/0.13-0.33=)\ 215\) fires in the UK and 187 fires in the EU that are confined to the sofa of origin and result in the replacement of the sofa but do not have fire emissions included as LCA input.

### Table B-5. Number of fires assuming a 10 year half life and that the change in "confined to item" and "confined to room" depends solely on FR treatment of the sofas.

<table>
<thead>
<tr>
<th></th>
<th>UK</th>
<th>European</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary Fires</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Small Fires</td>
<td>215 fires/million sofas</td>
<td>187 fires/million sofas</td>
</tr>
<tr>
<td>Fires starting in sofa</td>
<td>0.33 fires/million sofas</td>
<td>28.3 fires/million sofas</td>
</tr>
<tr>
<td>Fires confined to sofa</td>
<td>0.55*0.33 = 0.18</td>
<td>0.41*28.3 = 11.6</td>
</tr>
<tr>
<td>Fires starting in sofa confined to room</td>
<td>0.36*0.33 = 0.118</td>
<td>0.5*28.3 = 14.1</td>
</tr>
<tr>
<td>Fires starting in sofa confined to building</td>
<td>0.09*0.33 = 0.030</td>
<td>0.09*28.3 = 2.5</td>
</tr>
<tr>
<td>Secondary Fires</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fires confined to living room not starting in sofa</td>
<td>69</td>
<td>69</td>
</tr>
<tr>
<td>Fires confined to building</td>
<td>115</td>
<td>115</td>
</tr>
</tbody>
</table>

In the LCA model it is assumed that on average half the mass of the sofas are consumed during a primary sofa fire, while 90% of the mass is consumed in the secondary fires. All sofas are assumed to be involved in the fire after 50% of its life time (on average). This also means that 50% of the sofas that have been involved in a fire must be replaced.

### Fire experiments and LCA input data

LCA input based on fire experiments is difficult to define at best. In the furniture case study our aim was to use emission data from the sofa fires as input for the secondary and primary sofa fires. In the case of dioxin and furan emissions in the UK cases, however, the total production in the room experiments was less than in the corresponding sofa experiments, which indicate that, the UK Sofa fires did not truly reflect a secondary sofa fire. This is due to the fact that the conditions in the fire tests on the UK sofas did not mimic the conditions of these sofas burning in a flashed over room where the temperature is high and thus less dioxins and furans are produced. It was therefore decided to use the emissions from the individual sofa fire tests for all species except dioxins, furans, PBDE and DBDE emissions. For these species the emissions from the room experiments was used for secondary sofa fires. Since the chlorinated dioxins were about the same in all three room experiments it was decided that these were due to the room and not to the sofa. In some cases the emissions were in very close agreement with the emissions from the blank test. These emissions were set to zero. The non-FR room was the only room that gave any brominated dioxins, the Br-FR room only gave brominated furans. It is believed that the brominated dioxins in the non-FR case were caused by the old books...
used in that experiment and therefore the brominated dioxin emissions were set to 0 as in
the P-FR and Br-FR room so as not to skew the results unnecessarily.

In the LCA analysis the dioxins and furans were represented as TCDD and TBDD
equivalents. The TCDD equivalent were calculated according to ITEq. The TBDD
equivalent was calculated based on contributions from both dibenzodioxins and furans
and were based on the TCDD factors for the chlorinated equivalent. This is based on the
assumption that the relative toxicity of the brominated dibenzodioxins and furans is the
same as that for the chlorinated equivalent. In lieu of full data this should be a reasonable
assumption.
References


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8 Tabulated data from UK Home Office ordered specifically for this study (1996).


14 Personal communication with Jens Thiesen, Laboratory Head, NKT Cables, 2000.


17 http://www.statistics.gov.uk/
http://www.safety.odpm.gov.uk/fire/rds/index.htm

Effectiveness of the Furniture and Furnishings (Fire)(Safety) Regulation 1988, Government Consumer Safety Research, DTI


Statistics specially prepared for this project supplied by Polymer Research Centre, UK

www.forsakringsforbundet.com

"Räddningstjänst i siffror", Rescue service in numbers, Räddningsverket Karlstad Sweden, available only in Swedish

Appendix C: Warehouse test study

A small test study was conducted in order to assess the appropriateness of the guidelines. This appendix presents the results from that case study which was conducted on warehouses. This test study was conducted to evaluate the guidelines and therefore only one version of the functional unit was modelled and no comparison between different versions of the functional unit was made which is the normal use of the Fire-LCA method. In addition only CO₂ and particulate emissions were included in the analysis. The emission data used was estimated based on an assumed fire scenario.

Goal and Scope

The scope of the test study is to assess whether the guidelines contain sufficient information for a group of people familiar with LCA analysis and fire science to conduct a Fire-LCA analysis. Therefore only one version of the functional unit was modelled and no comparison between different versions of the functional unit was made which is the recommended use of the Fire-LCA method.

Selection of the functional unit

The functional unit employed in this example is the entire warehouse. This is the simplest possible choice and therefore meaningful in an illustrative example; in a broader context one could choose, e.g., “storage capacity for a specified amount of timber”.

The warehouse is assumed to have a lifetime of 25 years.

The building and its contents

The building to be studied is a warehouse for the storage of timber at a planing mill. The structure consists of a steel framework covered with a fabric made of a mixture of polyester and PVC plastics. The floor is made of asphalt. This type of construction has been developed by Best-Hall Oy of Kälviä, Finland. However, the building described here is purely fictional and is assumed not to represent any actual warehouse either existing or planned.

A schematic view of the building is shown in Figure C-1. The length \( L \) of the building is 36.3 m and the width \( W \) is 22 m, which gives a floor area of 800 m². There is a 7 m wide sliding door at one end of the building. The various heights shown in Figure C-1 are listed in the caption.

The building is unheated, and it is therefore assumed that the use of the building causes no environmental impact. The use of energy and resources and the generation of emissions and waste are only related to the construction of the building.

The steel framework has a weight of 19 000 kg and a surface area of 800 m². The steel parts are painted with epoxy paint with a film thickness of 100 µm. The steel parts do not have fire protection.

The framework is covered with a fabric made of a mixture of polyester and PVC plastics. The total weight of the fabric is 1200 kg. The fabric melts at elevated temperatures; thus, it is expected that a hole will be formed in any region, which is in contact with hot fire
gases or flames during a fire thereby facilitating venting of heat and fire gases in the case of a fire.

![Figure C-1](image1)

**Figure C-1** A schematic view of the warehouse to be analyzed in this study. The dimensions are: $W = 22$ m, $H_1 = 7.7$ m, $H_2 = 4.9$ m, $H_3 = 5.9$ m, $H_4 = 4.0$ m.

The building is used for the storage of rough and finished sawn timber. The timber has already been seasoned before it is brought to the warehouse and is therefore stored in tight bundles, the sizes of which are approximately $1$ m x $1$ m x $6$ m. In the fire scenario presented in the next chapter, the bundles are assumed to burn only on the outer surfaces. Thus, the analysis presented in this study is not valid for timber stored in open stacks for drying.

![Figure C-2](image2)

**Figure C-2** A schematic view of the storage of timber in the warehouse and the assumed location of ignition point. The dimensions are: $H = 2.5$ m, $H_T = 3$ m, $W_1 = 8$ m, $W_2 = 1$ m, $W_T = 6$ m.

The timber is assumed to be stored according to the scheme shown in Figure C-2. There is a 1 m clearance between the bundles and the sidewalls of the building due to the presence of structural members, and an 8 m wide passageway in the middle for the movement of the bundles using a forklift. The bundles are piled to a height of 3 m. The vertical distance $H$ from the top of the pile to the roof framework varies between 1 m (near the side wall) and 2.5 m (at the passageway). The total volume of timber in the warehouse is $2 \times 6 \times 3 \times 36 \text{ m}^3 = 1300 \text{ m}^3$. Assuming a density of 500 kg/m$^3$ and a heat of combustion of 20 MJ/kg for the timber, the mass of the timber is calculated as...
650 metric tons and the energy content as 13 000 GJ which is equal to a fire load of 16 000 MJ/m², which is a very high value, approx 30 times the average value of a office building\(^2\). The assumed location of the ignition point is also shown in Figure C-2.

**System boundaries**

The system boundary employed in this example is shown in Figure C-3. The situation is greatly simplified and only the most essential parts needed to illustrate the Fire-LCA approach have been included, as will be discussed below.

**Figure C-3** The system boundary employed in the warehouse example. Recycling of steel is taken into account, but the other materials are assumed to be manufactured from virgin raw materials.

Figure C-3 shows that recycling processes are partially taken into account in the example studied here. The recycling of steel is included according to the recycling model developed by the International Iron and Steel Institute (IISI) with 95 \% as recycling rate and 93.5 \% as yield ratio. The other materials are assumed to be manufactured from virgin raw materials.
As will be discussed below, the available statistical data is not sufficient enough to differentiate between primary and secondary fires. Thus, all fires are treated in a similar manner and will lead to the replacement of burned and damaged material.

For the warehouse, only 50% of the replacement materials are included in the LCA analysis; for the timber, 100% are included. This difference is based on the fact that a fire is equally likely at any instant during the lifetime of the building, and therefore only causes an average reduction of 50% in the lifetime of the building materials (cf. Chapter 4.4), whereas the timber stored in the warehouse is always at the beginning of its service life, and any amount lost in a fire will therefore have to be 100% replaced.

The building is unheated and was assumed not to require any particular renovations or maintenance during its lifetime. Thus, the normal use of the building was not associated with any resource use or emissions.

**Parameters to be considered**

The parameters considered in this example are energy use and emissions. To simplify the example, only the emissions of CO2 and particulates are included. CO2 is included since it is a major product from combustion reactions; thus, the uncertainties associated with the prediction of the amount of CO2 emissions from fires are smaller than the uncertainties associated with many other pollutants. Particulates are included since particulate emissions from fires have been estimated to be a significant source of pollution. To compute the yield of pollutants from the burning of the materials employed in this example, the yields as summarised in Table C-1 were used.

**Table C-1  Particle and CO2 yield from combusted material**

<table>
<thead>
<tr>
<th>Material</th>
<th>CO2 yield [kg/kg]</th>
<th>particulate yield [kg/kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Paint</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Fabric</td>
<td>2.0</td>
<td>0.05</td>
</tr>
<tr>
<td>Timber</td>
<td>1.6</td>
<td>0.01</td>
</tr>
</tbody>
</table>

Emissions from the burning of the paint will be ignored in this example. This is not quite realistic; however, the total amount of paint is small and the error is therefore quite small. The yield factors employed for fabric and timber are comparable to the values employed by Persson and Simonson.

The input data for energy use and CO2 and particulate emissions in manufacturing and transportation are taken from LCA studies carried out by VTT for the Finnish building industry. The methodology is described in Anon (2004). To compute the energy use and emissions due to transportation, it was assumed that steel will be transported 100 km by road, paint 400 km by road and fabric 1000 km by sea and 1000 km by road to the assembly site.

**Fire scenario**

Usually when conducting a Fire-LCA one constructs a statistical fire model with three different sizes of primary fires, i.e. confined to the product itself, confined to the room
and confined to the building. In this case the entire building is one big fire cell and it is therefore not realistic to use these classes of fire size.

The objective of this chapter is to describe a simplified fire scenario that was used in the Life Cycle Analysis calculations in this test study. The main outcome of the exercise is to evaluate the amount of material that will be destroyed by the fire. The amount of material will be used as input both in computing the emissions of harmful pollutants and in computing the amount of materials that must be repaired or replaced as a consequence of the fire.

Since the main purpose of this exercise is to give an illustrative example of the methodology proposed for the Fire LCA model, the fire scenario will be quite simple. It must be emphasized that the fire scenario presented here does not fulfill the needs of a complete Fire LCA analysis, and definitely does not meet the needs of an evaluation of other fire safety issues related to warehouse fires.

The fire scenario presented results in the complete destruction of the warehouse. In reality, fires of such severity are quite unusual, and most fires will be extinguished much earlier. Here the idea is to achieve a realistic estimate of the amount of materials destroyed in a fire by first giving a description of the worst-case fire scenario and then combining it with statistical information on the extent of fire damages in real fires. The statistical information will be presented in the next chapter.

List of assumptions made in the development of the fire scenario

The development of the fire scenario is based on the following assumptions:

(1) The fire is assumed to ignite at the floor level of the passageway in the vicinity of the timber bundles, as shown in Figure C-2. Once ignited, the fire will spread upwards and sideways along the faces of the timber bundles. The spreading rate of the fire can be expected to be fairly moderate since the fuel consists of massive bundles of timber. However, rapid spreading may occur if the ignition takes place in or near the vertical gap between the end faces of the bundles.

(2) The fire is assumed to grow according to the $t^2$-law:

$$\dot{Q} = \dot{Q}_0 \left(\frac{t}{t_g}\right)^2$$  \hspace{1cm} (C.1)

where $\dot{Q}$ is the heat release rate, $\dot{Q}_0$ is the reference value of the heat release rate (1 MW) and $t_g$ is the growth time. It is assumed here that $t_g = 300$ s, which corresponds to a medium rate of growth.

(3) It is assumed that the density of wood is 500 kg/m$^3$ and the heat of combustion is 20 MJ/kg. It is further assumed that the heat release rate per unit area of burning surface is 150 kW/m$^2$, which corresponds to a recession of the burning surface at a rate of 0.9 mm/min.

(4) It is assumed that fresh air is being supplied to the flame at a sufficient rate so as not to be a limiting factor, and that no hot layer will be formed in the upper part of the warehouse. These assumptions appear to be realistic considering that the fire is burning in a
very large warehouse and that the roof of the warehouse is made of a fabric which is expected to react to hot fire gases or contact with a flame by forming a hole, through which the hot gases escape due to buoyancy forces.

(5) It is assumed that the temperature of the gas in the fire plume can be computed using the method presented by Alpert. Thus, the maximum gas temperature at a vertical distance $H$ above the burning fuel is obtained from

$$T = T_0 + c\hat{Q}^{2/3}H^{-5/3}$$  \hspace{1cm} (C.2)

where $T_0$ is the ambient temperature, $c$ is a constant and $\hat{Q}$ is the heat release rate. The value of $c$ is $16.9 \text{ Kms}^{5/3}\text{kW}^{2/3}$. When the behaviour of the steel framework of the roof structure is evaluated, $H$ is measured from the top of the pile of timber bundles to the lowest part of the steel framework in the roof structure above the fire, as shown in Figure C-2. When the behaviour of the roof fabric is evaluated, $H$ is measured from the top of the pile of timber bundles to the highest part of the steel framework in the roof structure above the fire.

Alpert’s equation is based on work related to convection flows above a point source of heat. In the case studied here, the fire plume is being generated by a fire, which has spread over a considerable area on the surfaces of a pile of timber bundles. Thus, the results obtained using Alpert’s equation should be regarded as approximate. In particular, Alpert’s equation predicts extremely high gas temperatures for points located at a small vertical distance from a very large fire. In reality, it is more reasonable to assume that the temperatures in the fire plume do not exceed the flame temperature, which can be expected to be approximately $900 - 1100 \ ^\circ\text{C}$.

**Description of the fire scenario**

Using the assumptions listed in the previous section, the evolution of the fire is as described in Table C-2. It is assumed that the fire may be extinguished at any instant during the first twenty minutes after ignition. Naturally, the extent of damages will depend on the timing of the intervention.

**Table C-2 Fire scenario evolution**

<table>
<thead>
<tr>
<th>Time after ignition [min]</th>
<th>Description of events</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Heat release rate is 160 kW. Burning area is approximately 1 m$^2$. It is assumed that the fire has now spread upwards to the top of the pile, and that the equation of Alpert can be used from this point onwards to estimate gas temperature at different heights above the fire. According to Alpert’s equation, the temperature is 85 $^\circ\text{C}$ at the lowest level of the roof structure and 50 $^\circ\text{C}$ at the level of the roof fabric. The total heat release so far is 6.4 MJ, which corresponds to the complete combustion of 0.3 kg of wood. It is assumed that the fire has so far caused no damage at all to the building and only very small damage to the contents.</td>
</tr>
<tr>
<td>4</td>
<td>Heat release rate is 640 kW. Burning area is approximately 4 m$^2$. Alpert’s equation predicts a temperature of 220 $^\circ\text{C}$ at the lowest level of the roof structure and 120 $^\circ\text{C}$ at the level of the roof fabric. Roof fabric and painted surface of steel members are damaged in the area above the fire.</td>
</tr>
<tr>
<td>Time after ignition [min]</td>
<td>Description of events</td>
</tr>
<tr>
<td>--------------------------</td>
<td>----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>6</td>
<td>Heat release rate is 1400 kW. Burning area is approximately 10 m². If the burning were to take place only on the side of the pile of the timber bundles, then the width of the burning area would be 3 m. Such a rapid sideways spreading of the fire does not seem likely. However, the fire may have spread in the horizontal gaps between timber bundles piled on top of each other, and, depending on the location of the ignition, in the vertical gaps between the ends of timber bundles. Alpert’s equation predicts a temperature of 370 °C at the lowest level of the roof structure and 200 °C at the level of the roof fabric. Steel members in the roof framework may be distorted due to thermal expansion.</td>
</tr>
<tr>
<td>8</td>
<td>Heat release rate is 2600 kW. Burning area is approximately 17 m². Alpert’s equation predicts a temperature of 540 °C at the lowest level of the roof structure and 310 °C at the level of the roof fabric. It seems likely that the critical temperature of the roof framework is being reached, at least for the frame that is located directly above the fire. It is also assumed that a hole has formed in the roof fabric and hot gases are flowing out.</td>
</tr>
<tr>
<td>12</td>
<td>Heat release rate is 5800 kW. Burning area is approximately 38 m². Alpert’s equation predicts a temperature of 930 °C at the lowest level of the roof structure. From this point on, it is assumed that Alpert’s equation is no more valid and the temperature at the roof level above the fire is equal to the flame temperature (approximately 900 - 1100 °C). Extensive damage to the roof structure is expected to occur.</td>
</tr>
<tr>
<td>20</td>
<td>Heat release rate is 16 000 kW. The building is assumed to be a total loss.</td>
</tr>
</tbody>
</table>

**Probability values for LCA calculations**

**Probability of ignition**

The probability of ignition is estimated using the equation

\[ f = f'^* A \]  \hspace{1cm} (C.3)  

where \( f \) is the probability of ignition \((1/a)\), \( f'^* \) is the ignition frequency \((1/m²a)\) and \( A \) is the floor area of the building \((m²)\).

The ignition frequency is estimated using the generalized Barrois model

\[ f'^* = c_1 A^r + c_2 A^s \]  \hspace{1cm} (C.4)  

where \( c_1, r, c_2 \) and \( s \) are adjustable parameters. Analysis of data on warehouse fires in Finland during the period 1996–1999 has resulted in the following values for the parameters: \( c_1 = 3.82 \text{ m}^2.16/a, r = -2.08, c_2 = 2 \cdot 10^{-6} \text{ m}^{-1.9}/a, s = -0.057 \). Using these values and a floor area of 800 m², the ignition frequency is

\[ f'^* = 3.82 \cdot 800^{-2.08} + 2 \cdot 10^{-6} \cdot 800^{-0.05} \frac{1}{\text{m}^2a} = 4.9 \cdot 10^{-6} \frac{1}{\text{m}^2a} \]  \hspace{1cm} (C.5)
and the probability of ignition becomes

$$f = 4.9 \cdot 10^{-6} \frac{1}{\text{m}^2 \text{a}} \cdot 800 \text{ m}^2 = 0.004 \frac{1}{\text{a}}$$

(C.6)

In other words, a fire is expected to occur once in 250 years. This value covers all ignitions from all possible causes, both the primary fires and the secondary fires as defined in Section 4.2.

Statistics of warehouse fires in Finland in 1996-2001

Statistics of warehouse fires in Finland in 1996–2001 were collected from the database PRONTO, which is being maintained by the Ministry of the Interior. During this period of six years, there were 770 warehouse fires. The fires were distributed as summarised in Table C-3.

<table>
<thead>
<tr>
<th>Floor area of the building [m²]</th>
<th>&lt; 10</th>
<th>10 – 40</th>
<th>40 – 160</th>
<th>&gt; 160</th>
<th>TOTAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 500 or unknown</td>
<td>485</td>
<td>140</td>
<td>53</td>
<td>5</td>
<td>683</td>
</tr>
<tr>
<td>500 – 2000</td>
<td>31</td>
<td>6</td>
<td>12</td>
<td>8</td>
<td>57</td>
</tr>
<tr>
<td>2000 – 8000</td>
<td>10</td>
<td>1</td>
<td>0</td>
<td>5</td>
<td>16</td>
</tr>
<tr>
<td>&gt; 8000</td>
<td>8</td>
<td>2</td>
<td>0</td>
<td>4</td>
<td>14</td>
</tr>
<tr>
<td>TOTAL</td>
<td>534</td>
<td>149</td>
<td>65</td>
<td>22</td>
<td>770</td>
</tr>
</tbody>
</table>

It can be seen that a vast majority of the fires occurred in small warehouses. Most of those fires only caused minor losses, and the distribution of fires causing larger losses shows a strong decreasing trend. This seems quite natural: the distribution of the values of the warehouses and the goods stored in them presumably also shows a decreasing trend, and many of the small warehouses are in fact just small sheds with such a limited value that large losses appear to be impossible. In other words, the number of fires causing large losses in small warehouses must be small because the number of possible scenes for such destruction is quite limited.

However, there were also 87 fires that occurred in warehouses with a floor area of 500 m² or above. Of those 87 fires, roughly one half caused minor losses, while the other half were quite evenly distributed between different categories. Losses in excess of 160 000 euros seem to be just as likely as losses between 10 000 and 40 000 euros, or losses between 40 000 and 160 000 euros. It can be speculated that in the case of large warehouses, the number of fires causing large losses is not being limited by the number of suitable objects; thus, if the fire grows beyond a certain size, then any amount of losses will be equally likely. Of course, the amount of data is not really large enough to test this conclusion.

It is to be noted that the statistical data are not sufficiently detailed to distinguish between primary fires and secondary fires. Indeed, in the warehouse case such a division may not be as relevant as in the case of a consumer product. In the example studied here, it will be assumed that all warehouse fires can be regarded as primary fires; thus, the replacement of both the warehouse itself and its contents will be included in the LCA calculations.
Probability distribution of fire damages in the warehouse analysed in this study

Based on the fire scenario and probability considerations presented in previous sections, the probability distribution for fire damages as presented in Table C-4 is adopted:

Table C-4  Probability distribution for fire damages

<table>
<thead>
<tr>
<th>Fire severity*</th>
<th>Fraction of fires</th>
<th>Steel</th>
<th>Fabric</th>
<th>Timber</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[%]</td>
<td>Burned [%]</td>
<td>Damaged [%]</td>
<td>Burned [%]</td>
</tr>
<tr>
<td>1</td>
<td>50</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>10</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>10</td>
<td>2</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td>10</td>
<td>10</td>
<td>20</td>
<td>50</td>
</tr>
<tr>
<td>5</td>
<td>10</td>
<td>30</td>
<td>40</td>
<td>60</td>
</tr>
<tr>
<td>6</td>
<td>10</td>
<td>100</td>
<td>100</td>
<td>–</td>
</tr>
</tbody>
</table>

* There is a rough correspondence between the fire severities 1-6 and the different stages of fire evolution presented in Table C-2

Paint is not included in the table. It is assumed that the damages to paint are equal to the damages to steel.

For each material, there are three different outcomes that are possible:

- “burned” means material which has been consumed by the fire. In Life Cycle Analysis, this means that there will be negative consequences both due to harmful emissions that are generated during the burning and due to the need to replace the burned materials and to dispose of the fire residues. Steel does not burn, and therefore the “burned” column for steel is empty.

- “damaged” means material which has not burned but has been damaged due to heat or smoke. In Life Cycle Analysis, this means that there will be no harmful emissions due to burning, but there will be negative consequences due to the need to replace the damaged materials and to dispose of the residues.

- Material, which is neither “burned” nor “damaged” is assumed not to be affected by the fire, and will cause no negative consequences in the Life Cycle Analysis. This category is not shown in the table, and therefore the amounts do not always sum up to 100 %.

It may be noted that even in a large fire, the fraction of materials actually burning is often quite small. This can be seen especially in the column for timber. Using the numerical values adopted in this study, the amount of timber stored in the warehouse is 650 metric tons, and the complete combustion of 20 % of this quantity of timber will correspond to a total heat release of 2600 GJ. This corresponds to a 120 MW fire burning for six hours. This simple computation illustrates how little fuel load is actually needed for a very serious fire.
Results

The results are compiled in tables C-5 to C-7. In all tables, there are some discrepancies in the computation of the sums, these are due to round-off errors. Please note that due to the simplifications and assumptions made in this test study the results should not be regarded as a complete LCA or Fire-LCA analysis. The aim of the study is to investigate whether the Guidelines provide sufficient detail for an experienced LCA practitioner to apply the Fire-LCA model.

CO₂ emissions

The emissions of CO₂ are shown in Table C-5. The emissions are presented in three classes: emissions from the phases normally included in LCA calculations, emissions from fires, and emissions from the replacement of materials burned and damaged in fires.

<table>
<thead>
<tr>
<th></th>
<th>Construction materials</th>
<th>Building contents</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manufacturing and transportation (traditional LCA)</td>
<td>6240</td>
<td>9360</td>
</tr>
<tr>
<td>Emissions from fires</td>
<td>40</td>
<td>0</td>
</tr>
<tr>
<td>Replacement of materials burned and damaged due to fires</td>
<td>90</td>
<td>70</td>
</tr>
<tr>
<td>SUM</td>
<td>63600</td>
<td>9420</td>
</tr>
</tbody>
</table>

It can be seen that CO₂ emissions mostly originate from the construction of the warehouse and from the transportations associated with the construction. The amount of CO₂ emissions from the manufacturing of steel appears to be fairly low considering that the mass of steel is much higher than the mass of the other construction materials. This is due to the fact that a very high recycling ratio was assumed for the steel.

Particulate emissions

The emissions of particulates are shown in Table C-6. The emissions are presented in three classes: emissions from the phases normally included in LCA calculations, emissions from fires, and emissions from the replacement of materials burned and damaged in fires.

It can be seen that the amount of particulate emissions from fires are of the same order of magnitude as the particulate emissions which originate from the construction of the warehouse and from the transportations associated with the construction. This is due to the fact that a rather large amount of timber was assumed to be burned in the largest fires included in the fire scenario. It would be a worthwhile objective to carry out a more detailed assessment of possible fire scenarios and the amount of timber being burned in the fires but this was not included the scope of this project.
### Table C-6  Emissions of particulates

<table>
<thead>
<tr>
<th></th>
<th>Construction materials</th>
<th>Building contents</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manufacturing and</td>
<td>8.5</td>
<td>9.6</td>
</tr>
<tr>
<td>transportation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(traditional LCA)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Emissions from fires</td>
<td>1.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Replacement of materials</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>burned and damaged</td>
<td></td>
<td></td>
</tr>
<tr>
<td>due to fires</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SUM</td>
<td>9.6</td>
<td>9.7</td>
</tr>
</tbody>
</table>

As with the CO$_2$ emissions, the amount of particulate emissions from the manufacturing of steel appears to be fairly low. Again, this is due to the fact that a very high recycling ratio was assumed for the steel.

### Energy use

The use of energy is shown in Table C-7. Fires are not assumed to consume any energy, and the energy use is therefore presented in two classes: energy use during the phases normally included in LCA calculations and energy use during the replacement of materials burned and damaged in fires.

### Table C-7  Energy use

<table>
<thead>
<tr>
<th></th>
<th>Construction materials</th>
<th>Building contents</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manufacturing and</td>
<td>112</td>
<td>192</td>
</tr>
<tr>
<td>transportation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(traditional LCA)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Replacement of materials</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>burned and damaged</td>
<td></td>
<td></td>
</tr>
<tr>
<td>due to fires</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SUM</td>
<td>113</td>
<td>193</td>
</tr>
</tbody>
</table>

It can be seen that most of the energy use is associated with the construction of the warehouse and from the transportations associated with the construction.

### Conclusions

The Nordic method for the Life Cycle Assessment including fire considerations was applied to a simplified warehouse example. In this example, the method worked well and the results seem to be reasonable. More case studies are needed to fully assess the applicability of the method.
It was found that most of the CO₂ emissions and energy use were due to the manufacturing of the warehouse and due to the transportations associated with the manufacturing. The particulate emissions from fires were found to be comparable to the particulate emissions due to the manufacturing of the warehouse and due to the transportations associated with the manufacturing.

The main source of emissions from fires was the burning of the timber stored in the warehouse. In this example, the emissions from the burning of the building materials appear to be quite small compared to emissions from burning timber.

The greatest difficulties in this example were in defining the fire scenarios and in collecting the input data for the LCA calculations. It is to be expected that advances in fire statistics and in fire and environmental sciences will lead to progress in both these areas.
References

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