LCA Methodology

Human Health Damages due to Indoor Sources of Organic Compounds and Radioactivity in Life Cycle Impact Assessment of Dwellings

Part 1: Characterisation Factors

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Preamble. In this series of two papers, a methodology to calculate damages to human health caused by indoor emissions from building materials is presented and applied. **Part 1** presents the theoretical foundation of the indoor emission methodology developed, as well as characterisation factors calculated for 36 organic compounds, radon and gamma radiation. **Part 2** calculates damage scores of building materials with the characterisation factors presented in part 1. The relevancy of including indoor air emission in the full damage scores at a material level and a dwelling level is also quantified and discussed.

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Abstract

Goal, Scope and Background. Methodologies based on life cycle assessment have been developed to calculate the environmental impact of dwellings. Human health damage due to exposure to substances emitted to indoor air are not included in these methodologies. In order to compare this damage with human health damages associated with the rest of the life cycle of the dwelling, a methodology has been developed to calculate damages to human health caused by pollutants emitted from building materials.

Methods. Fate, exposure and health effects are addressed in the calculation procedure. The methodology is suitable for organic substances, radon and elements emitting gamma radiation. The (Dutch reference) dwelling used in the calculation was divided in three compartments: crawl space, first floor and second floor. Fate factors have been calculated based on indoor and outdoor intake fractions, dose conversion factors or extrapolation from measurements. Effect factors have been calculated based on unit risk factors, (extrapolated) effect doses or linear relationship between dose and cancer cases. Damage factors are based on disability adjusted life years (DALYs).

Results and Discussion. Characterisation factors have been calculated for 36 organic compounds, radon and gamma radiation emitted by building materials applied in a Dutch reference dwelling. For organic compounds and radon, the characterisation factors of emissions to the second floor are 10–20% higher than the characterisation factors of emissions to the first floor. For the first and second floor, the characterisation factors are dominated by damage to human health as a result of indoor exposure. The relative contribution of carcinogenic and non-carcinogenic effects to the characterisation factors is generally within one order of magnitude, and up to three orders of magnitude for formaldehyde.

Conclusion. Health effects due to indoor exposure to pollutants emitted from building materials appear to be dominant in the characterisation factors over outdoor exposure to such pollutants. The health effects of emissions of organic compounds and gamma radiation in the crawl space are very small compared to the health effects of emissions into the other compartments. Using the characterisation factors calculated in this study, it is possible to calculate the human health damage due to emissions of substances and radiation emitted to indoor air and compare this damage with damages to human health associated with the rest of the life cycle of the material. This is the subject of part II of this research.

Keywords: Building materials; dwellings; gamma radiation; human health damages; indoor pollutants; life cycle impact assessment; organic compounds; radioactivity; radon

Introduction

In life cycle impact assessment (LCIA), several methods have been developed to calculate the impact of emissions of harmful components on human health [1–7]. These methods take into account outdoor sources of contamination. A method to evaluate the impact of indoor sources on human health due to indoor exposure is, however, still missing [8,9]. The reason for this absence is that LCIAs usually do not take into account local effects of products on users [8].

However, environmental comparisons and improvements for building products may be biased by excluding the impact of indoor air pollution. For instance, human health damage scores of concrete compared to wood may be underestimated by excluding indoor air emissions of radon and gamma radiation. Another example is that the positive influence on human health of mechanical indoor air ventilation in buildings is not accounted for by disregarding impacts of indoor air pollution.

Table 1: Human health impact categories [7]

Human health impact category	Compound	Exposure
Carcinogenic effects	Organic compounds	Indoor and outdoor
Non-carcinogenic effects	Organic compounds	Indoor and outdoor
Effects of ionising radiation	Radioactive compounds	Indoor and outdoor
Respiratory effects due to ozone creation	Organic compounds	Outdoor
Effects of climate change	All	Outdoor
Effects of ozone layer depletion	All	Outdoor

The impact of indoor pollution on human health may be an important factor for the LCIA of dwellings, because people live in houses for a great part of their lives. The Dutch Health Council for instance estimated the number of casualties due to lung cancer as a result of exposure to radon in the Netherlands at 800 per year [10]. In a review of radiation exposure in the Netherlands, it appears that nearly 50% of the total average annual dose per capita of the Dutch population originates from radon or gamma radiation from building materials [11]. Apparently, the exclusion of indoor exposure to radioactive elements originating from building materials leads to an underestimation of the human health risks in the life cycle assessment of dwellings. Something similar may hold for organic pollutants. For instance, Sexton et al. showed an increased indoor concentration of fifteen organic compounds in three urban communities, if compared with outdoor concentrations [12].

This article presents characterisation factors for 36 organic compounds, radon and gamma-radiating elements present in building materials. The characterisation factors are calculated for a Dutch reference dwelling [13,14]. It is assumed that this dwelling in occupied by three persons. Fate, effects and damages are incorporated in the characterisation factor calculations [7]. Fate factors of organic compounds and radon are calculated using an indoor airflow and exposure model for dwellings. Exposure in both indoor and outdoor environment is considered. Effect factors are calculated using unit risk factors for carcinogenic effects [7], no observed effect levels (NOELs) and lowest observed effect levels (LOELs) for non-carcinogenic effects [15], and epidemiological data for ionising radiation [1]. Damages to human health are expressed in disability adjusted life years (DALYs) [1,4,7]. The impact categories that are taken into account in this research are given in **Table 1**.

Carcinogenic effects, non-carcinogenic effects and effect of ionising radiation are relevant for exposure in both indoor and outdoor environment. Respiratory effects caused by ozone creation, effects of climate change and effects of ozone layer depletion are only relevant for exposure in outdoor environment.

Parameter values used in this methodology are given in **Appendix 2** (online edition only <DOI: http://dx.doi.org/10.1065/lca2004.12.194.1>).

1 Methodology

1.1 Calculation procedure

In the LCIA methodology, characterisation factors can be used to calculate the combined environmental damage occurring in the life cycle of a product [16]. In figure 1, an overview of the steps from emission to damage is given. For compounds in building products, characterisation factors can be used to link (activity) concentrations to human health damage. For radon, the total amount of radon exhaled during the lifetime of the building material is used instead of activity concentration. The damage score for the use phase of building material p can then be calculated by Eq. (1):

$$DS_{p,u} = \sum_{x} M_{x,p} \cdot Q_x \tag{1}$$

where $DS_{p,u}$ is the damage score associated with the use phase of building material p (DALY·kg_p^{-1}); $M_{x,p}$ is the (activity) concentration of compound x in building material p or the total amount of radon exhaled during the lifetime of building material p (kg·kg_p^{-1} or Bq·kg_p^{-1}); and Q_x is the characterisation factor of compound x (e.g. DALY·kg^{-1} or DALY·Bq^{-1}).

The calculation of the (activity) concentration of compounds in building materials is described in the second part of this research [17] (**Fig. 1**).

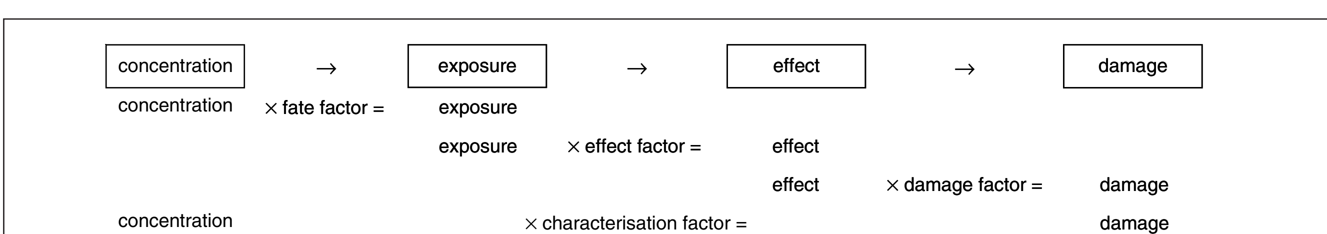

Fig. 1: Overview of the steps from concentration in building materials to damage (adapted from [18])

As the calculations regard damage to human health, the characterisation factors for compound x can be calculated by Eq. (2) [7]:

$$Q_x = \sum_j \left(F_{x,j} \cdot \sum_k E_{x,k,j} \cdot D_{x,k} \right) \quad (2)$$

where F_x is the fate factor of substance x (or radiation) for impact category j (dimensionless or Sv·Bq^{-1}); $E_{x,k,r}$ is the effect factor of substance x (or radiation) for impact category j for human health damage category k (cases·kg^{-1} or cases·Sv^{-1}); and $D_{x,k}$ is the damage factor of substance x (or radiation) for human health damage category k (DALY·case^{-1}).

1.2 Fate factors

1.2.1 Organic pollutants

The dose received by humans as a result of a concentration of organic compound x in building material p situated in dwelling compartment a can be calculated by multiplying the concentration of this compound in a building material with a fate factor $F_{x,p,a,r}$, see Eq. (3):

$$F_{x,p,a,r} = F_{x,p \to air} \cdot F_{x,a,r,air \to human} \quad (3)$$

where $F_{x,p,a,r}$ is the fate factor of compound x in material p emitted to compartment a causing human exposure via intake pathway r (–); $F_{x,p \to air}$ is the fraction of the concentration of compound x in material p emitted to air (–); and $F_{x,a,r,air \to human}$ is the intake fraction via intake pathway r of substance x emitted in compartment a (–). We assume that $F_{x,p \to air}$ approaches 1 over the lifetime of the building [19].

The intake pathways r that are regarded in this study are inhalation in the indoor environment (*ii*), inhalation in the outdoor environment (*oi*) and oral uptake in outdoor environment (*oo*).

Fate factors for pollutants emitted to outdoor air are commonly calculated with multimedia fate models [2–5]. For the indoor environment, these models cannot be used, because the transport routes and sinks inside the dwelling differ from those outside.

To calculate concentrations of compounds emitted indoors, the dwelling is divided into crawlspace, first floor and second floor. In **Fig. 2**, an overview of these compartments and the airflows in the house is given. It is assumed that the concentrations in the rooms of one compartment are similar. As convective transport has the dominating effect on concentrations in dwellings [20], diffusive transport and indoor degradation are not included in the fate factor calculations. Furthermore, in these calculations average Dutch meteorological conditions and ventilation behaviour are assumed.

The intake fraction via indoor inhalation can be calculated using the cumulative inhalation rate and the airflows in the dwelling by Eq. (4):

$$F_{x,a,ii,air \to human} = \frac{IR}{f_{e,a}} \cdot N_a \quad (4)$$

where $F_{x,a,ii,air \to human}$ is the intake fraction via indoor inhalation of substance x emitted in compartment a (–). IR is the inhalation rate of humans (m^3·y^{-1}); $f_{e,a}$ is the effective outgoing airflow for an emission to compartment a (m^3·y^{-1}); and N_a is the number of persons living in the dwelling (–).

The effective outgoing airflow $f_{e,a}$ is the weighed sum of the airflows leaving all compartments regarding an emission in compartment a. It reflects the pollutant transport between the compartments and the time fraction the occupants spend in the compartments. The calculation of the effective outgoing airflow for an emission in the three compartments is described in **Appendix 1** (online edition only <DOI: http://dx.doi.org/10.1065/lca2004.12.194.1>).

The intake fraction via outdoor inhalation by all humans can be calculated by Eq. (5):

$$F_{x,a,oi,air \to human} = F_{x,a,indoor \to outdoor} \cdot F_{x,oi,outdoor \to human} \quad (5)$$

where $F_{x,a,oi,air \to human}$ is the intake fraction via outdoor inhalation of organic compound x emitted in compartment a (–); $F_{x,a,indoor \to outdoor}$ is the fraction of organic compound x emitted to compartment a that is transported from indoor air to outdoor air (–); and $F_{x,oi,outdoor \to human}$ is the intake fraction via outdoor inhalation of organic compound x emitted to air (–).

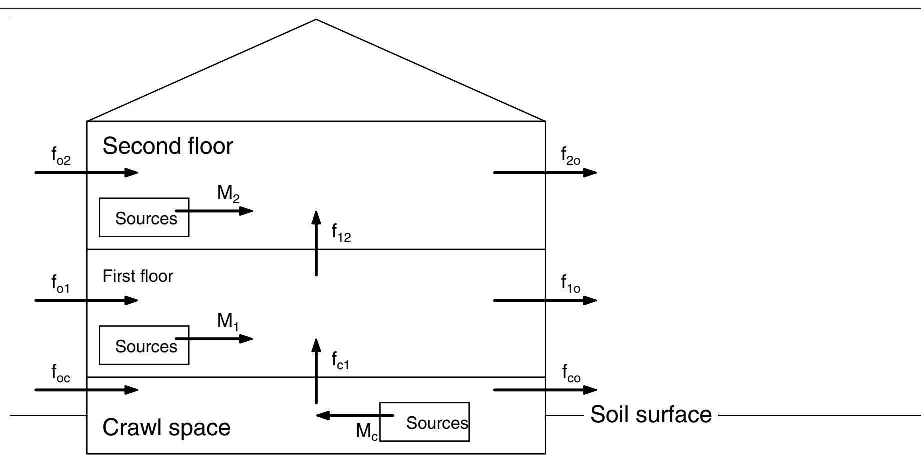

Fig. 2: Overview of the different compartments of the dwelling and the airflows

The intake fraction via ingestion can be calculated by Eq. (6):

$$F_{x,a,oo,air\rightarrow human} = F_{x,a,indoor\rightarrow outdoor} \cdot F_{x,oo,outdoor\rightarrow human} \quad (6)$$

where $F_{x,a,oo,air\rightarrow human}$ is the intake fraction via ingestion of substance x emitted in compartment a (–); and $F_{x,oo,outdoor\rightarrow human}$ is the intake fraction via ingestion of substance x (–).

The fraction of the organic pollutants emitted from indoor air to outdoor air is equal to the fraction of the indoor emission not adsorbed by the occupants of the dwelling, see Eq. (7):

$$F_{x,a,indoor\rightarrow outdoor} = 1 - F_{x,a,ii,air\rightarrow human} \quad (7)$$

Outdoor human intake fractions of 36 organic compounds often found in indoor air are given in **Appendix 2** (online edition only <DOI: http://dx.doi.org/10.1065/lca2004.12.194.1>). A summary of the fate factors for organic compounds is given in **Table 2**. The fate factors for all organic compounds are given in Appendix 2.

1.2.2 Radon

The human dose in indoor air as a result of radon exhaled from building material p situated in dwelling compartment a can be calculated by Eq. (8):

$$F_{Rn,a,ii,air\rightarrow human} = \frac{CF_d}{f_{e,a}} \cdot N_a \quad (8)$$

where $F_{Rn,a,ii,air\rightarrow human}$ is the fate factor, representing the conversion of the presence of radon in indoor air to dose received by the occupants, for radon emitted in compartment a (Sv·Bq^{-1}); and CF_d is the dose conversion factor (Sv·y^{-1}·Bq^{-1}·m^3) [21].

The fate factor for radon adsorbed via inhalation in outdoor air can be calculated by Eq. (9):

$$F_{Rn,a,oi,air\rightarrow human} = F_{Rn,a,indoor\rightarrow outdoor} \cdot F_{Rn,oi,outdoor\rightarrow human} \quad (9)$$

where $F_{Rn,a,oi,air\rightarrow human}$ is the fate factor for radon exhalation in compartment a to human dose of radon adsorbed in outdoor air via inhalation (Sv·Bq^{-1}); $F_{Rn,a,indoor\rightarrow outdoor}$ represents the fraction of radon exhaled to compartment a that is transported from indoor air to outdoor air (–); and $F_{Rn,oi,outdoor\rightarrow human}$ represents the conversion of the presence of radon in outdoor air to dose received by all humans (Sv·Bq^{-1}).

Because radon has a relatively high half-life (3.8 days) in view of the ventilation rate, it is assumed that $F_{Rn,a,indoor\rightarrow outdoor}$ approaches 1. $F_{Rn,oi,outdoor\rightarrow human}$ is equal to $1.6\cdot10^{-11}$ Sv·Bq^{-1} [7]. The fate factors for radon are given in Table 2.

1.2.3 Gamma radiation

Gamma radiation originates from the decay of the isotopes ^{226}Ra, ^{232}Th and ^{40}K in stony building materials. In order to calculate fate factors for these three isotopes, five prerequisites need to be fulfilled:

1. The radiation field is uniform and homogenous within each of the three compartments of the dwelling (crawl space, first floor and second floor; see Fig. 2). According to Blaauboer & Pruppers, this is the case for average dwellings [22];
2. The calculations made for a standard room (dimensions 5 x 4 x 2.8 m and a wall thickness of 20 cm) are valid for all rooms in the dwelling. This is in line with the findings of Koblinger that there are no significant differences for rooms with widely different dimensions [23,24];
3. The gamma radiation has only effect in the compartment in which it is emitted. This assumption has been empirically shown to hold for situations with separating walls thicker than 20 cm [24];
4. There is a linear relationship between the intensity of the radiation field and the density of the building material. According to Koblinger, this is valid for densities up to 2500 kg·m^{-3} [24];
5. There is a linear relationship between the intensity of the radiation field and the thickness of the walls. Koblinger showed that this is valid for wall thickness up to 30 cm [24].

As these five prerequisites are met in the Dutch reference dwelling, the fate factor for gamma-radiating element x emitted in compartment a is equal to (Eq. (10)):

$$F_{x\in gamma,p,a} = \frac{k_x}{M_s} \cdot SF \cdot t_a \cdot N_a \cdot LT_p \quad (10)$$

where $F_{x\in gamma,p,a}$ is the fate factor for gamma-radiating element x emitted from product p in compartment a (Sv·Bq^{-1}); k_x is the conversion factor for isotope x to calculate the free-in-air dose rate from the activity concentration in the building materials in the room (Gy·y^{-1}·Bq^{-1}·kg); M_s is the total

Table 2: Summary of fate factors of organic compounds, radon and gamma radiation

Substance	CAS-nr	Unit	Crawlspace	First floor	Second floor	Outdoor	
			$F_{x,c,ii}$ [a]	$F_{x,1,ii}$	$F_{x,2,ii}$	$F_{x,oi}$ [b]	$F_{x,oo}$
Organic compounds		–	$1.3\cdot10^{-5}$	$2.6\cdot10^{-2}$	$3.1\cdot10^{-2}$	$< 6\cdot10^{-4}$	$< 3\cdot10^{-5}$
Radon	10043-92-2	Sv·Bq^{-1}	$5.4\cdot10^{-14}$	$1.1\cdot10^{-10}$	$1.3\cdot10^{-10}$	$1.6\cdot10^{-11}$	0
Gamma-radiating elements:							
^{226}Ra	13982-63-3	Sv·Bq^{-1}	0	$1.2\cdot10^{-8}$	$7.1\cdot10^{-9}$	0	0
^{232}Th	7440-29-1	Sv·Bq^{-1}	0	$1.3\cdot10^{-8}$	$7.9\cdot10^{-9}$	0	0
^{40}K	13966-00-2	Sv·Bq^{-1}	0	$1.0\cdot10^{-9}$	$6.2\cdot10^{-10}$	0	0

[a] $F_{x,a,ii}$: Fate factor of compound x emitted to compartment a (crawl space, first floor or second floor) causing human exposure via indoor inhalation
[b] $F_{x,r}$: Fate factor of compound x emitted from indoor air to outdoor air, causing human exposure via pathway r (outdoor inhalation or outdoor oral uptake)

mass of the building materials in the standard room (kg); SF is the average air-organ shielding factor for gamma radiation (Sv·Gy^{-1}); t_a is the time fraction spent by the occupants in compartment a (–); and LT_p is the lifetime of the assessed product (y). The calculation of the fate factor for gamma radiation have been carried out in this research with an assumed lifetime of products of 75 year, which is the lifetime of most stony materials applied in a dwelling [14].

The effects of gamma radiation emitted to outdoor environment on human health are not considered in this study, because of the relatively low population density outdoor.

The fate factors for ^{226}Ra, ^{232}Th and ^{40}K are given in Table 2.

1.3 Effect factors

1.3.1 Carcinogenic effects of organic compounds

For emissions in the indoor environment, the inhalation pathway is of primary importance.

The effect factor for the carcinogenic effects of organic compounds is calculated (Eq. (11)) using the low-dose slope factor q_1^* [25], also often referred to as unit risk factor UR [4,7]:

$$E_{x,c,i} = \frac{0.5 \cdot UR_{x,c,i}}{LT_h \cdot IR} \qquad (11)$$

where $E_{x,c,i}$ is the effect factor of organic compound x adsorbed via inhalation for human health damage due to carcinogenic effects (cancer cases·kg^{-1} intake of substance x via inhalation); $UR_{x,c,i}$ is the unit risk factor of carcinogenic effects for inhalation of substance x (cases·kg^{-1}·m^3); and LT_h is the lifetime of humans (y).

For the emissions to outdoor air, both inhalation and ingestion are important. The carcinogenic effect factor after ingestion can be calculated by Eq. (12) [25] :

$$E_{x,c,o} = \frac{0.5 \cdot UR_{x,c,o}}{LT_h \cdot BW} \qquad (12)$$

where $E_{x,c,o}$ is the carcinogenic effect factor of organic compound x after ingestion (cancer cases·kg^{-1}); $UR_{x,c,o}$ is the unit risk factor of carcinogenic effects for oral uptake of substance x (cases·kg^{-1}·kg$_{bw}$·y); and BW is the human bodyweight (kg$_{bw}$).

Calculated carcinogenic effect factors for organic compounds are given in **Appendix 2** (online edition only <DOI: http://dx.doi.org/10.1065/lca2004.12.194.1>). Carcinogenic effect factors range from $5.6 \cdot 10^{-4}$ to $3.6 \cdot 10^{-2}$ cases·kg^{-1} for the considered organic compounds.

1.3.2 Non-carcinogenic effects of organic compounds

For non-carcinogenic effects, the effect factor is calculated from the ED$_{10}$, the effect dose where 10 percent of the test animals shows a response [15]. In line with the approach of Pennington et al. [15], it is assumed that at low exposure concentrations of a specific organic compound, the dose-response relationship is linear with no threshold.

The effect factor for uptake via inhalation of contaminant x can be calculated by Eq. (13):

$$E_{x,nc,i} = \frac{\beta_{x,nc,i}}{LT_h \cdot IR} \qquad (13)$$

where $E_{x,nc,i}$ is the non-carcinogenic effect factor of organic compound x after inhalation (cases·kg^{-1}); and $\beta_{x,nc,i}$ is the extrapolated slope factor of substance x for non-carcinogenic effects as a result of uptake via inhalation (cases·kg^{-1}·m^3 of substance x).

The non-carcinogenic effect factor after ingestion of organic compound x can be calculated by Eq. (14):

$$E_{x,nc,o} = \frac{\beta_{x,nc,o}}{LT_h \cdot BW} \qquad (14)$$

where $E_{x,nc,o}$ is the non-carcinogenic effect factor of organic compound x after ingestion (cases·kg^{-1}); and $\beta_{x,nc,o}$ is the extrapolated slope factor of substance x for non-carcinogenic effects as a result of uptake via ingestion (cases·kg^{-1}·kg$_{bw}$·y of substance x).

The extrapolated slope factor for non-carcinogenic effects as a result of uptake via inhalation is calculated by Eq. (15) [15]:

$$\beta_{x,nc,i} = \frac{CF_{ED_{10}} \cdot CF_{sc}}{EL_{x,nc,i}} \qquad (15)$$

where CF_{ED10} is the conversion factor from no observed effect level (NOEL) or lowest observed effect level (LOEL) to ED$_{10}$ (cases); CF_{sc} is the conversion factor from subchronic to chronic effects (–); and $EL_{x,nc,i}$ is either the NOEL or LOEL of substance x for non-carcinogenic effects via inhalation, depending on data availability (kg·m^{-3}).

The extrapolated slope factor for non-carcinogenic effects as a result of uptake via ingestion can be calculated by Eq. (16) [15]:

$$\beta_{x,nc,o} = \frac{CF_{ED_{10}} \cdot CF_{sc} \cdot CF_{ah}}{EL_{x,nc,o}} \qquad (16)$$

where CF_{ah} is the conversion factor to account for differences between test animals and humans (–); and $EL_{x,nc,o}$ is either the NOEL or LOEL of substance x for non-carcinogenic effects via oral uptake, depending on data availability (kg·kg$_{bw}$·y^{-1}).

When effect levels for either inhalation or ingestion are unavailable, route-to-route extrapolation can be applied, based on the effect factors for oral uptake respectively for uptake via inhalation. The relationship between the extrapolated slope factors can be expressed by Eq. (17):

$$\beta_{x,nc,i} = \beta_{x,nc,o} \cdot \frac{IR}{BW} \cdot \frac{FA_i}{FA_o} \quad (17)$$

where FA_i is the fraction adsorbed via inhalation (–); and FA_o is the fraction adsorbed via ingestion (–).

Calculated non-carcinogenic effect factors for organic compounds are given in **Appendix 2** (online edition only <DOI: http://dx.doi.org/10.1065/lca2004.12.194.1>). Non-carcinogenic effect factors range from $1 \cdot 10^{-4}$ to 3 cases·kg^{-1} for the considered organic compounds. Appendix 2 presents the underlying data.

1.3.3 Radioactivity

The effect factor for radioactive exposure is calculated by Eq. (18) [26]:

$$E_{x,k} = c_k \quad (18)$$

where $E_{x,k}$ is the effect factor of either radon or gamma radiation for human health damage due to the effects of ionising radiation on tissue or organ k (cases·Sv^{-1}); and c_k is the number of cases of cancers affecting tissue or organ k due to a dose of radiation (cases·Sv^{-1}).

The values of c_k used here are those given by Frischknecht et al. [1]. In the Eco-Indicator 99 methodology, 13 tissues and organs are considered [7]. For clarity, only the combined effect and damage factors for radioactive pollutants are calculated. The value of the combined effect and damage factors is 1.5 DALY·kg^{-1} for all radioactive pollutants [1].

1.4 Damage factors

The disability adjusted life years (DALY) concept has been developed by the World Health Organisation [27], and has been adjusted for use in LCIA [4].

For all contaminants and affected tissues or organs, the calculation of the damage factor regarding human health is the same (Eq. (19)):

$$D_{x,k} = DALY_{x,k} \quad (19)$$

where $D_{x,k}$ is the damage factor of substance x for human health damage to tissue or organ k (y·case^{-1}); and $DALY_{x,k}$ is the disability adjusted life years of substance x per incidence case to organ k (y·case^{-1}).

The damage scores for organic compounds are derived from Hofstetter and Pennington et al. and are given in **Appendix 2** (online edition only <DOI: http://dx.doi.org/10.1065/lca2004.12.194.1>) [4,15]. The damage factors for carcinogenic substances range from 12.1 to 16.5 y·case^{-1} [4]. For non-carcinogenic effects, there are three severity categories, with damage factors of respectively 6.7, 0.67 and 0.067 [15]. Most substances assessed in this study have a damage factor of 0.67 y·case^{-1}.

1.5 Other impact categories

For human health damages due to respiratory effects, climate change and ozone layer depletion, the characterisation factors given by the Eco-Indicator 99 methodology can be used [7], corrected for the fraction adsorbed by the occupants of the dwelling (Eq. (20)):

$$Q_{x,r} = Q_{x,r,EI99} \cdot F_{x,p \rightarrow air} \cdot \left(1 - F_{x,a,ii,air \rightarrow human}\right) \quad (20)$$

where $Q_{x,r,EI99}$ is the characterisation factor according to the Eco-Indicator 99 methodology (DALY·kg^{-1}). The characterisation factors $Q_{x,r,EI99}$ are given in **Appendix 2** (online edition only <DOI: http://dx.doi.org/10.1065/lca2004.12.194.1>).

1.6 Characterisation factors

The fate factors, effect factors and damage factors are combined to calculate characterisation factors (equation 2). Also the contributions of the health damage due to indoor exposure to pollutants emitted to the indoor air are calculated. The results are given in **Table 3**.

2 Discussion

The indoor air model can be tested against empirical data only to a limited extend. An important element in such tests is the comparison of calculated and measured indoor concentrations of substances. In this respect, there are only data available for radon. From a preliminary study, it appeared that the concentrations of radon in the reference dwelling calculated with this methodology are roughly the same as the concentrations found in a national survey in the Netherlands [28,29].

Uncertainties in the fate factor calculation of organic compounds and radon are caused by the use of average airflow characteristics and time fractions spent in the different compartments, which may differ due to differences in occupant behaviour. Furthermore, the effect of sinks in the dwelling is not taken into account. This may lead to an overestimation of the human health damage. For the calculation of the fate factors for gamma radiation, the uncertainties lie in the assumption of a linear relationship between material mass and dose rate, the conversion factors from activity concentration to dose rate, user behaviour and the fact that gamma radiation originating in adjacent compartments is not taken into account. The last assumption might result in an underestimation of up to 25% when separating walls have a thickness of less than 20 centimetres [22]. Important factors that determine the results of the calculations are ventilation rate, number of occupants and time fractions spent in the different compartments. The calculations presented in this study are valid only for single-family dwellings.

In the carcinogenic effect factors of organic pollutants, sources of uncertainties are the assumed non-threshold behaviour of the dose-response relations, the high variability between risk estimates from different sources for the same substance and the extrapolation of missing unit risk factors (for oral uptake of formaldehyde), as carried out by Hofstetter [4]. The same sources of uncertainties are valid for non-carcinogenic effects of organic pollutants [15]. For the effect factors for radioactivity, the uncertainties in the epidemiological data are the main source of uncertainty [1].

The damage factors are calculated taking account of the duration of a disease or a period of life lost due to premature death, and weighing the severity of disease. As to the matter of dura-

Table 3: Characterisation factors of organic compounds, radon and gamma radiation and fraction of health damage caused by indoor exposure

Substance	CAS-nr	Unit	Characterisation factors			Fraction indoor		
			$Q_{x,c}$ [a]	$Q_{x,1}$	$Q_{x,2}$	$FI_{x,c}$ [b]	$FI_{x,1}$	$FI_{x,2}$
Organic compounds								
Acetaldehyde	75-07-0	$DALY{\cdot}kg^{-1}$	$2.3{\cdot}10^{-6}$	$1.8{\cdot}10^{-3}$	$2.2{\cdot}10^{-3}$	39%	100%	100%
Acetone	67-64-1	$DALY{\cdot}kg^{-1}$	$2.4{\cdot}10^{-7}$	$3.7{\cdot}10^{-5}$	$4.5{\cdot}10^{-5}$	8%	99%	100%
Benzaldehyde	100-52-7	$DALY{\cdot}kg^{-1}$	$1.4{\cdot}10^{-6}$	$2.7{\cdot}10^{-5}$	$3.2{\cdot}10^{-5}$	1%	95%	96%
Benzene	71-43-2	$DALY{\cdot}kg^{-1}$	$4.4{\cdot}10^{-6}$	$4.2{\cdot}10^{-3}$	$5.0{\cdot}10^{-3}$	46%	100%	100%
n-Butanol	71-36-3	$DALY{\cdot}kg^{-1}$	$1.4{\cdot}10^{-6}$	$4.3{\cdot}10^{-6}$	$4.9{\cdot}10^{-6}$	0%	69%	73%
2-Butoxy ethanol	111-76-2	$DALY{\cdot}kg^{-1}$	$1.1{\cdot}10^{-6}$	$2.3{\cdot}10^{-4}$	$2.7{\cdot}10^{-4}$	10%	100%	100%
Butyl acetate	123-86-4	$DALY{\cdot}kg^{-1}$	$5.4{\cdot}10^{-7}$	$3.6{\cdot}10^{-5}$	$4.3{\cdot}10^{-5}$	3%	99%	99%
Carbon tetrachloride	56-23-5	$DALY{\cdot}kg^{-1}$	$1.2{\cdot}10^{-3}$	$1.1{\cdot}10^{-2}$	$1.3{\cdot}10^{-2}$	0%	89%	91%
o-Cresol	95-48-7	$DALY{\cdot}kg^{-1}$	$2.1{\cdot}10^{-6}$	$7.7{\cdot}10^{-5}$	$9.1{\cdot}10^{-5}$	2%	97%	98%
Cumene	98-82-8	$DALY{\cdot}kg^{-1}$	$1.1{\cdot}10^{-6}$	$1.6{\cdot}10^{-5}$	$1.9{\cdot}10^{-5}$	1%	93%	94%
1,1-Dichloroethane	75-34-3	$DALY{\cdot}kg^{-1}$	$3.8{\cdot}10^{-7}$	$1.8{\cdot}10^{-5}$	$2.1{\cdot}10^{-5}$	2%	98%	98%
o-Dichlorobenzene	95-50-1	$DALY{\cdot}kg^{-1}$	$2.2{\cdot}10^{-6}$	$1.1{\cdot}10^{-4}$	$1.3{\cdot}10^{-4}$	2%	98%	98%
p-Dichlorobenzene	106-46-7	$DALY{\cdot}kg^{-1}$	$2.2{\cdot}10^{-6}$	$5.0{\cdot}10^{-5}$	$5.9{\cdot}10^{-5}$	1%	96%	96%
Dichloromethane	75-09-2	$DALY{\cdot}kg^{-1}$	$4.4{\cdot}10^{-6}$	$1.3{\cdot}10^{-3}$	$1.5{\cdot}10^{-3}$	14%	100%	100%
Diethyl phthalate	84-66-2	$DALY{\cdot}kg^{-1}$	$2.2{\cdot}10^{-6}$	$3.9{\cdot}10^{-5}$	$4.6{\cdot}10^{-5}$	1%	95%	95%
Ethyl acetate	141-78-6	$DALY{\cdot}kg^{-1}$	$4.6{\cdot}10^{-7}$	$4.6{\cdot}10^{-6}$	$5.4{\cdot}10^{-6}$	0%	90%	92%
Ethyl benzene	100-41-4	$DALY{\cdot}kg^{-1}$	$1.6{\cdot}10^{-6}$	$8.4{\cdot}10^{-5}$	$1.0{\cdot}10^{-4}$	3%	98%	99%
Ethylene glycol	107-21-1	$DALY{\cdot}kg^{-1}$	$8.8{\cdot}10^{-7}$	$4.7{\cdot}10^{-5}$	$5.6{\cdot}10^{-5}$	3%	98%	99%
Formaldehyde	50-00-0	$DALY{\cdot}kg^{-1}$	$8.8{\cdot}10^{-6}$	$1.2{\cdot}10^{-2}$	$1.4{\cdot}10^{-2}$	63%	100%	100%
n-Hexane	110-54-3	$DALY{\cdot}kg^{-1}$	$1.1{\cdot}10^{-6}$	$2.3{\cdot}10^{-4}$	$2.8{\cdot}10^{-4}$	10%	100%	100%
Methanol	67-56-1	$DALY{\cdot}kg^{-1}$	$2.9{\cdot}10^{-7}$	$7.7{\cdot}10^{-6}$	$9.1{\cdot}10^{-6}$	1%	96%	97%
Methyl ethyl ketone	78-93-3	$DALY{\cdot}kg^{-1}$	$8.3{\cdot}10^{-7}$	$3.7{\cdot}10^{-5}$	$4.4{\cdot}10^{-5}$	2%	98%	98%
Naphthalene	91-20-3	$DALY{\cdot}kg^{-1}$	$3.0{\cdot}10^{-6}$	$1.8{\cdot}10^{-3}$	$2.2{\cdot}10^{-3}$	29%	100%	100%
Phenol	108-95-2	$DALY{\cdot}kg^{-1}$	$2.3{\cdot}10^{-6}$	$3.2{\cdot}10^{-4}$	$3.8{\cdot}10^{-4}$	7%	99%	99%
Phenyl chloride	108-90-7	$DALY{\cdot}kg^{-1}$	$2.2{\cdot}10^{-6}$	$1.0{\cdot}10^{-4}$	$1.2{\cdot}10^{-4}$	2%	98%	98%
Propylene glycol monomethyl ether	107-98-2	$DALY{\cdot}kg^{-1}$	$7.9{\cdot}10^{-7}$	$1.7{\cdot}10^{-6}$	$1.9{\cdot}10^{-6}$	0%	56%	60%
Styrene	100-42-5	$DALY{\cdot}kg^{-1}$	$2.6{\cdot}10^{-6}$	$9.4{\cdot}10^{-4}$	$1.1{\cdot}10^{-3}$	18%	100%	100%
Tetrachloroethylene	127-18-4	$DALY{\cdot}kg^{-1}$	$2.6{\cdot}10^{-6}$	$9.7{\cdot}10^{-4}$	$1.2{\cdot}10^{-3}$	18%	100%	100%
Toluene	108-88-3	$DALY{\cdot}kg^{-1}$	$1.4{\cdot}10^{-6}$	$1.4{\cdot}10^{-4}$	$1.7{\cdot}10^{-4}$	5%	99%	99%
1,2,4-Trichlorobenzene	120-82-1	$DALY{\cdot}kg^{-1}$	$4.1{\cdot}10^{-6}$	$1.6{\cdot}10^{-3}$	$1.9{\cdot}10^{-3}$	19%	100%	100%
1,1,1-Trichloroethane	71-55-6	$DALY{\cdot}kg^{-1}$	$8.3{\cdot}10^{-5}$	$9.8{\cdot}10^{-5}$	$1.0{\cdot}10^{-4}$	0%	17%	20%
Trichloroethylene	79-01-6	$DALY{\cdot}kg^{-1}$	$9.3{\cdot}10^{-7}$	$3.0{\cdot}10^{-4}$	$3.6{\cdot}10^{-4}$	16%	100%	100%
Trichloromethane	67-66-3	$DALY{\cdot}kg^{-1}$	$2.9{\cdot}10^{-5}$	$1.2{\cdot}10^{-2}$	$1.4{\cdot}10^{-2}$	19%	100%	100%
Triethyl amine	121-44-8	$DALY{\cdot}kg^{-1}$	$1.6{\cdot}10^{-7}$	$3.3{\cdot}10^{-4}$	$3.9{\cdot}10^{-4}$	98%	100%	100%
Vinyl chloride	75-01-4	$DALY{\cdot}kg^{-1}$	$3.2{\cdot}10^{-6}$	$1.8{\cdot}10^{-3}$	$2.1{\cdot}10^{-3}$	27%	100%	100%
Xylenes	1330-20-7	$DALY{\cdot}kg^{-1}$	$2.4{\cdot}10^{-6}$	$2.2{\cdot}10^{-5}$	$2.6{\cdot}10^{-5}$	0%	89%	91%
Radon	10043-92-2	$DALY{\cdot}Bq^{-1}$	$2.4{\cdot}10^{-11}$	$1.9{\cdot}10^{-10}$	$2.3{\cdot}10^{-10}$	0%	88%	89%
Gamma-radiating elements								
^{226}Ra	13982-63-3	$DALY{\cdot}Bq^{-1}$	0	$1.8{\cdot}10^{-8}$	$1.1{\cdot}10^{-8}$		100%	100%
^{232}Th	7440-29-1	$DALY{\cdot}Bq^{-1}$	0	$2.0{\cdot}10^{-8}$	$1.2{\cdot}10^{-8}$		100%	100%
^{40}K	13966-00-2	$DALY{\cdot}Bq^{-1}$	0	$1.6{\cdot}10^{-9}$	$9.4{\cdot}10^{-10}$		100%	100%

[a] $Q_{x,a}$: Characterisation factor of compound *x* emitted in compartment *a* (crawl space, first floor or second floor)
[b] $FI_{x,a}$: Fraction of total human health damage caused by indoor exposure to compound *x* emitted in compartment *a* (crawl space, first floor or second floor)

tion, the main source of uncertainty is the uncertainty that occurs in the epidemiological data used to determine the years living disabled and years of life lost. As to weighing the severity of diseases, the subjectivity thereof is another source of uncertainty [4]. The default values of 6.7, 0.67 and 0.067 $y{\cdot}case^{-1}$ for the damage factors of the three severity categories of non-carcinogenic effects have a high uncertainty [15].

From the results presented in Table 2, it appears that the indoor fate factors for emissions to the crawl space are negligible for organic compounds and gamma radiation compared to the indoor fate factors for emissions to the first and second floor. Also the fate factor for indoor exposure is much larger than for outdoor exposure. However, according to Table 3, the health damage due to emissions of organic compounds in the crawl space cannot be disregarded in all cases because of the health damage caused by emissions to the outdoor air due to respiratory effects, climate change and ozone layer depletion. Furthermore, according to Table 3, it appears that for the first and second floor, the characterisation factors are dominated by damage to human health as a result of indoor exposure. This emphasizes the significance of this research.

Furthermore, it can be concluded that the mutual differences among the fate factors for outdoor intake of organic compounds are very small compared to the mutual differences among the fate factors for indoor intake. Therefore, it seems justified to use average fate factors for all organic compounds.

From **Table A4** and **Table A5** presented in **Appendix 2** (online edition only <DOI: http://dx.doi.org/10.1065/lca2004.12.194.1>), it can be derived that the relative contribution of carcinogenic and non-carcinogenic effects to the characterisation factors is generally within one order of magnitude, and up to three orders of magnitude for formaldehyde. This stresses the relevance of the addition of non-carcinogenic effects to the damage characterisation methodology of LCIA.

Finally, for organic compounds and radon, the characterisation factors of emissions to the second floor are 10% to 20% higher than the characterisation factors of emissions to the first floor. The calculations might be simplified by taking the average of the characterisation factors for the first floor and for the second floor. This difference is considered as not significant in the light of the uncertainties mentioned above. The relevancy of the results presented in this paper in the total life cycle is yet uncertain and is dealt with in the second part of this study.

3 Conclusion

In this paper, a fate model for indoor contaminants has been developed. Effect and damage factors for carcinogenic and non-carcinogenic effects of organic compounds originating from building materials and for carcinogenic effects of radon and gamma radiation are also calculated, based on the disability adjusted life years (DALY) methodology.

For 36 organic compounds, radon and three gamma-radiating elements, characterisation factors have been determined for human health damages due to emission to indoor air for the Dutch reference dwelling. It appears that for the first and second floor outdoor exposure to organic compounds and radioactivity originating from building materials is less important than indoor exposure. Furthermore, the health effects of emissions of organic compounds and gamma radiation in the crawl space are generally negligible compared to the health effects of emissions into the other compartments. The relative contribution of carcinogenic and non-carcinogenic effects to the characterisation factors is within up to three orders of magnitude, but generally within one order of magnitude. Finally, the differences between the fate factors of organic compounds are negligible as indoor fate plays a dominant role.

Using the characterisation factors calculated in this study, it is possible to calculate the human health damage due to emissions of substances and radiation emitted to indoor air and compare this damage with damages to human health associated with the rest of the life cycle of the material. This is the subject of part II of this research.

App. 1 and 2 can be found in the online-edition of this paper <DOI: http://dx.doi.org/10.1065/lca2004.12.194.1>

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Appendix 1: The calculation of the effective outgoing airflows

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The dwelling is divided into three compartments, assuming the same concentrations in the rooms in one compartment. In figure 1, an overview of the different compartments of the house and the airflows is given.

The airflows from the crawlspace to the indoor area on the first floor can be calculated by Eq. A1 [1]:

$$f_{c1} = \frac{of_1^{\,2} \cdot \Delta p_{1c}}{n_1 \pi \cdot 8\eta \cdot Lf_1} \cdot A_f \tag{A1}$$

where f_{c1} is the airflow from the crawlspace to the first floor ($m^3 \cdot y^{-1}$); of_1 is the fraction of openings in the floor of the first floor (-); ΔP_{1c} is the air pressure difference between the first floor and the crawl space (Pa); n_1 is the number of gaps in the floor of the first floor per floor area (m^{-2}); η is the dynamic viscosity of air (Pa·y); Lf_1 is the floor thickness of the first floor (m); and A_f is the floor area (m^2).

In an analogous way, the airflow from the first floor to the second flow can be calculated by Eq. A2:

$$f_{12} = \frac{of_2^{\,2} \cdot \Delta p_{21}}{n_2 \pi \cdot 8\eta \cdot Lf_2} \cdot A_f \tag{A2}$$

where f_{12} is the airflow from the first floor to the second floor ($m^3 \cdot y^{-1}$); of_2 is the fraction of openings in the floor of the second floor (–); ΔP_{21} is the air pressure difference between the second floor and the first floor (Pa); n_2 is the number of gaps in the floor of the second floor per floor area (m^{-2}); and Lf_2 is the floor thickness of the second floor (m).

In view of the domination of upward vertical draught, it is assumed that there is no downward airflow in common dwellings.

The calculation of the airflows between outdoor and indoor space is based on the Bernoulli equation. It is calculated by Eq. A3 [2]:

$$f_{oa} = c_{sy} \cdot Cd \cdot A_{oa} \cdot \sqrt{2 \cdot \Delta p_{oa} / \rho} \tag{A3}$$

where f_{oa} is the airflow between outdoor air and compartment a ($m^3 \cdot y^{-1}$); c_{sy} is the conversion coefficient from seconds to year ($s \cdot y^{-1}$); Cd is the discharge coefficient for the openings between outdoor air and compartment a (–); A_{oa} is the cross-sectional area of the openings between outdoor air and compartment a (m^2); ΔP_{oa} is the pressure difference between outdoor air and compartment a (Pa); and ρ is the air density ($kg \cdot m^{-3}$).

The airflows between outdoor and indoor space are calculated separately for all facades of the dwelling. At the facade on the windward side, the airflow is generally from outside to inside, and at the leeward side generally the reverse is true. It is assumed that A_{oa} is equal to the effective air leakage area $A_{L,oa}$ [2].

The pressure difference between outdoor air and compartment a consists of two parts (Eq. (A4)):

$$\Delta p_{oa} = \Delta p_{s,oa} + p_{w,oa} \tag{A4}$$

where $\Delta p_{s,oa}$ is the pressure difference between outdoor air and compartment a due to stack effect (Pa); and $p_{w,oa}$ is the wind pressure on the surface between outdoor air and compartment a (Pa).

The pressure difference between outdoor air and compartment a due to stack effect, $\Delta p_{s,oa}$ can be calculated by Eq. (A5):

$$\Delta p_{s,oa} = \rho \cdot g \cdot (H_{oa} - H_{NPL}) \cdot (T_{i,oa} - T_o) / T_o \tag{A5}$$

where H_{oa} is the average height of connection oa (m); H_{NPL} is the height of neutral pressure level (m); $T_{i,oa}$ is the indoor temperature for connection oa (K); and T_o is the outdoor temperature (K).

The wind pressure on the surface between outdoor air and compartment a, $p_{w,oa}$ can be calculated by Eq. (A6):

$$p_{w,oa} = ½ \cdot Cp_{oa} \cdot \rho \cdot V^2 \tag{A6}$$

where Cp_{oa} is the wind surface pressure coefficient for connection oa (–); and V is the wind speed ($m \cdot s^{-1}$). The wind surface pressure coefficient depends on the angle between the surface between outdoor air and compartment a and is given for several angles [2].

Based on the airflows defined above, the total ventilation rates of the different compartments can be calculated by Eqs. (A7,8,9):

$$vr_c = f_{oc} \tag{A7}$$

$$vr_1 = f_{o1} + f_{c1} \tag{A8}$$

$$vr_2 = f_{o2} + f_{12} \tag{A9}$$

where vr_c is the total ventilation rate of the crawl space ($m^3 \cdot y^{-1}$); f_{oc} is the airflow from outside to the crawl space ($m^3 \cdot y^{-1}$); vr_1 is the total ventilation rate of the first floor ($m^3 \cdot y^{-1}$); f_{o1} is the airflow from outside to the first floor ($m^3 \cdot y^{-1}$); vr_2 is the total ventilation rate of the second floor ($m^3 \cdot y^{-1}$); and f_{o2} is the airflow from outside to the second floor ($m^3 \cdot y^{-1}$). The airflows f_{oc}, f_{o1} and f_{o2} are calculated using Eq. (A3).

The effective outgoing airflows can then be calculated by Eqs. (A10,11,12):

$$f_{e,c} = \frac{1}{\dfrac{t_c}{vr_c} + \dfrac{t_1 \cdot f_{c1}}{vr_1 \cdot vr_c} + \dfrac{t_2 \cdot f_{12} \cdot f_{c1}}{vr_2 \cdot vr_1 \cdot vr_c}} = \frac{vr_c}{t_c + t_1 \cdot \dfrac{f_{c1}}{vr_1} + t_2 \cdot \dfrac{f_{c1}}{vr_1} \cdot \dfrac{f_{12}}{vr_2}} \tag{A10}$$

$$f_{e,1} = \frac{1}{\dfrac{t_1}{vr_1} + \dfrac{t_2 \cdot f_{12}}{vr_2 \cdot vr_1}} = \frac{vr_1}{t_1 + t_2 \cdot \dfrac{f_{12}}{vr_2}} \tag{A11}$$

$$f_{e,2} = \frac{1}{t_2 / vr_2} = \frac{vr_2}{t_2} \tag{A12}$$

where $f_{e,c}$ is the effective outgoing airflow of an emission to the crawl space (–); t_c is the time fraction spent in the crawl space (–); t_1 is the time fraction spent in the first floor (–); t_2 is the time fraction spent in the second floor (–); $f_{e,1}$ is the effective outgoing airflow of an emission to the first floor (-); and $f_{e,2}$ is the effective outgoing airflow of an emission to the second floor (–).

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Appendix 2: Background data

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In **Table A1**, the values of the parameters used in this study are given. In **Table A2**, data to calculate the characterisation factors for several organic compounds are given. The fate factors of all organic compounds are given in **Table A3**. The effect factors of organic compounds, radon and gamma-radiating elements are given in **Table A4**. The damage scores for organic compounds are given in **Table A5** [3,4]. The characterisation factors for human health damages due to respiratory effects, climate change and ozone layer depletion are given in **Table A6** [5].

Table A1: (Assumed) value for several parameters

Standard parameter	**Denotation**	**Value**	**Literature**
c_{sy}	Seconds per year	31557600 $s \cdot y^{-1}$	
G	Gravity constant	9.81 $m \cdot s^{-2}$	
η	Dynamic viscosity of air	$6.8 \cdot 10^{-13}$ Pa·y	
ρ	Air density (273 K)	1.29 $kg \cdot m^{-3}$	
Building-specific parameter	**Denotation**	**Assumed value**	**Literature**
A_f	Floor area	39 m^2	[6]
Ac_{oc}	Cross-sectional area of openings between outdoor and crawl space	0.0102 m^2	[2,7]
Ac_{co}	Cross-sectional area of openings between crawl space and outdoor	0.0102 m^2	[2,7]
Ac_{o1}	Cross-sectional area of openings between outdoor and first floor	0.00214 m^2	[2,7]
Ac_{1o}	Cross-sectional area of openings between first floor and outdoor	0.00206 m^2	[2,7]
Ac_{o2}	Cross-sectional area of openings between outdoor and second floor	0.00105 m^2	[2,7]
Ac_{2o}	Cross-sectional area of openings between second floor and outdoor	0.00105 m^2	[2,7]
H_c	Average height of crawl space	–0.05 m	
H_1	Average height of first floor	1.26 m	
H_2	Average height of second floor	3.77 m	
H_{NPL}	Height of neutral pressure level	2.51 m	
Lf_1	Floor thickness of first floor	0.23 m	[6]
Lf_2	Floor thickness of second floor	0.23 m	[6]
n_1	Number of gaps in floor of first floor	10	[1]
n_2	Number of gaps in floor of second floor	10	[1]
of_1	Fraction of openings in floor of first floor	$1.28 \cdot 10^{-5}$	[1,6]
of_2	Fraction of openings in floor of second floor	$1.28 \cdot 10^{-5}$	[1,6]
ΔP_{1c}	Air pressure difference between first floor and crawl space	4 Pa	
ΔP_{21}	Air pressure difference between second floor and first floor	4 Pa	
Occupant-dependent parameter	**Denotation**	**Assumed value**	**Literature**
N_a	Number of people living in dwelling	3	
t_c	Time fraction spent in crawl space	0	
t_1	Time fraction spent in first floor	0.5	
t_2	Time fraction spent in second floor	0.3	
Meteorological parameter	**Denotation**	**Assumed value**	**Literature**
Cp_{oc}, Cp_{o1}, Cp_{o2}	Wind surface pressure coefficient	0.7	[2]
Cp_{co}, Cp_{1o}, Cp_{2o}	Wind surface pressure coefficient	–0.14	[2]
$T_{i,c}$	Indoor temperature in crawl space	289 K	
$T_{i,1}$	Indoor temperature in first floor	293 K	
$T_{i,2}$	Indoor temperature in second floor	292 K	
T_o	Outdoor temperature	288 K	
V	Wind speed	5 $m \cdot s^{-1}$	
Other parameter	**Denotation**	**(Assumed) value**	**Literature**
BW	Average human bodyweight	70 kg	[4]
Cd	Discharge coefficient	1	[2]
CF_{ah} (dog)	Conversion factor to account for differences between dogs and humans	1.5	[8]
CF_{ah} (human)	Conversion factor to account for differences between species for humans	1	
CF_{ah} (mouse)	Conversion factor to account for differences between mice and humans	7.3	[8]
CF_{ah} (rat)	Conversion factor to account for differences between rats and humans	4.1	[8]
CF_d	Dose conversion factor	$2.1 \cdot 10^{-5}$ $Sv \cdot y^{-1} \cdot Bq^{-1} \cdot m^3$	[9]
$CF_{ED10,LOEL}$	Conversion factor from lowest observed effect level (LOEL) to ED_{10}	0.33 cases	[4]
$CF_{ED10,NOEL}$	Conversion factor from no observed effect level (NOEL) to ED_{10}	0.062 cases	[4]
$CF_{sc,chronic}$	Conversion factor from subchronic to chronic effects for effect levels measured for a chronic time period	1	[4]
$CF_{sc,subchronic}$	Conversion factor from subchronic to chronic effects for effect levels measured for a subchronic time period	3.3	[4]
FA_i	Fraction absorbed via inhalation	0.75	[8]
FA_o	Fraction adsorbed via oral uptake	1	[8]
IR	Human inhalation rate	4860 $m^3 \cdot y^{-1}$	
k_{Ra}	Conversion factor for ^{226}Ra to calculate the free-in-air dose rate	$6.94 \cdot 10^{-6}$ $Gy \cdot y^{-1} \cdot Bq^{-1} \cdot kg$	[10]
k_{Th}	Conversion factor for ^{232}Th to calculate the free-in-air dose rate	$7.79 \cdot 10^{-6}$ $Gy \cdot y^{-1} \cdot Bq^{-1} \cdot kg$	[10]
k_K	Conversion factor for ^{40}K to calculate the free-in-air dose rate	$6.1 \cdot 10^{-7}$ $Gy \cdot y^{-1} \cdot Bq^{-1} \cdot kg$	[10]
LT_h	Human lifetime	70 y	[3,4]
LT_p	Lifetime of products	70 y	
M_s	Total mass of the building materials in standard room	46500 kg	[10]
SF	Average air-organ shielding factor for gamma radiation	0.7 $Sv \cdot Gy^{-1}$	[11]

Table A2: Data to calculate the characterisation factors for organic compounds

Substance	CAS #	Uptake path	$F_{x,r,outdoor\rightarrow human}$ [a] [12] (–)	Effect level [c] ($mg \cdot m^{-3}$) [d] ($mg \cdot kg^{-1} \cdot day^{-1}$)	Criterion [b]	Duration
Acetaldehyde	75-07-0	inhalation	$3.3\cdot10^{-7}$	8.7 [c]	NOEL	subchronic
		oral	$8.4\cdot10^{-9}$	n/a		
Acetone	67-64-1	inhalation	$1.0\cdot10^{-5}$	n/a		
		oral	$6.8\cdot10^{-7}$	100 [d]	NOEL	subchronic
Benzaldehyde	100-52-7	inhalation	$1.2\cdot10^{-6}$	n/a		
		oral	$1.3\cdot10^{-6}$	143 [d]	NOEL	subchronic
Benzene	71-43-2	inhalation	$1.2\cdot10^{-5}$	8.6 [c]	LOEL	subchronic
		oral	$2.3\cdot10^{-8}$	n/a		
n-Butanol	71-36-3	inhalation	$2.6\cdot10^{-6}$	n/a		
		oral	$8.1\cdot10^{-7}$	125 [d]	NOEL	subchronic
2-Butoxy ethanol	111-76-2	inhalation	$9.6\cdot10^{-7}$	150 [c]	LOEL	subchronic
		oral	$1.2\cdot10^{-6}$	55 [d]	NOEL	subchronic
Butyl acetate	123-86-4	inhalation	$2.9\cdot10^{-6}$	95 [c]	LOEL	subchronic
		oral	$3.3\cdot10^{-8}$	n/a		
Carbon tetrachloride	56-23-5	inhalation	$5.3\cdot10^{-4}$	6.4 [c]	NOEL	chronic
		oral	$2.1\cdot10^{-7}$	1 [d]	NOEL	subchronic
o-Cresol	95-48-7	inhalation	$1.9\cdot10^{-7}$	n/a		
		oral	$4.8\cdot10^{-7}$	50 [d]	NOEL	subchronic
Cumene	98-82-8	inhalation	$1.1\cdot10^{-6}$	435 [c]	NOEL	subchronic
		oral	$7.2\cdot10^{-9}$	110 [d]	NOEL	subchronic
1,1-Dichloroethane	75-34-3	inhalation	$3.3\cdot10^{-5}$	366 [c]	NOEL	subchronic
		oral	$3.0\cdot10^{-8}$	n/a		
o-Dichlorobenzene	95-50-1	inhalation	$2.2\cdot10^{-5}$	60 [c]	NOEL	subchronic
		oral	$4.4\cdot10^{-7}$	43 [d]	NOEL	chronic
p-Dichlorobenzene	106-46-7	inhalation	$2.7\cdot10^{-5}$	67 [c]	NOEL	chronic
		oral	$2.1\cdot10^{-7}$	10 [d]	NOEL	subchronic
Dichloromethane	75-09-2	inhalation	$3.4\cdot10^{-5}$	3 [c]	NOEL	chronic
		oral	$4.3\cdot10^{-8}$	6 [d]	NOEL	chronic
Diethyl phthalate	84-66-2	inhalation	$2.6\cdot10^{-6}$	n/a		
		oral	$3.0\cdot10^{-5}$	100 [d]	NOEL	subchronic
Ethyl acetate	141-78-6	inhalation	$2.8\cdot10^{-6}$	n/a		
		oral	$5.8\cdot10^{-8}$	900 [d]	NOEL	subchronic
Ethyl benzene	100-41-4	inhalation	$3.0\cdot10^{-6}$	77 [c]	NOEL	subchronic
		oral	$9.2\cdot10^{-9}$	97 [d]	NOEL	subchronic
Ethylene glycol	107-21-1	inhalation	$4.0\cdot10^{-7}$	n/a		
		oral	$1.1\cdot10^{-5}$	40 [d]	NOEL	chronic
Formaldehyde	50-00-0	inhalation	$1.4\cdot10^{-6}$	0.12 [c]	NOEL	subchronic
		oral	$9.2\cdot10^{-6}$	15 [d]	NOEL	chronic
n-Hexane	110-54-3	inhalation	$1.1\cdot10^{-6}$	73 [c]	LOEL	chronic
		oral	$8.3\cdot10^{-10}$	n/a		
Methanol	67-56-1	inhalation	$6.9\cdot10^{-6}$	n/a		
		oral	$3.8\cdot10^{-6}$	500 [d]	NOEL	subchronic
Methyl ethyl ketone	78-93-3	inhalation	$5.6\cdot10^{-6}$	875 [c]	NOEL	chronic
		oral	$3.5\cdot10^{-7}$	1771 [d]	NOEL	subchronic
Naphthalene	91-20-3	inhalation	$9.8\cdot10^{-7}$	9.3 [c]	LOEL	chronic
		oral	$7.8\cdot10^{-8}$	52 [d]	ED10	subchronic
Phenol	108-95-2	inhalation	$7.2\cdot10^{-7}$	20 [c]	NOEL	subchronic
		oral	$3.7\cdot10^{-6}$	93 [d]	BMD10	chronic
Phenyl chloride	108–90–7	inhalation	$1.6\cdot10^{-5}$	341 [c]	LOEL	subchronic
		oral	$5.4\cdot10^{-8}$	19.5 [d]	NOEL	subchronic
Propylene glycol monomethyl ether	107–98–2	inhalation	$1.3\cdot10^{-6}$	658 [c]	NOEL	subchronic
		oral	$2.9\cdot10^{-6}$	n/a		
Styrene	100–42–5	inhalation	$4.9\cdot10^{-7}$	26 [c]	LOEL	chronic
		oral	$3.5\cdot10^{-9}$	12 [d]	NOEL	chronic
Tetrachloroethylene	127–18–4	inhalation	$5.5\cdot10^{-5}$	25 [c]	LOEL	chronic
		oral	$3.5\cdot10^{-8}$	16 [d]	NOEL	sub–acute
Toluene	108–88–3	inhalation	$3.6\cdot10^{-6}$	119 [c]	LOEL	chronic
		oral	$4.6\cdot10^{-9}$	223 [d]	LOEL	subchronic
1,2,4–Trichlorobenzene	120–82–1	inhalation	$2.0\cdot10^{-5}$	4 [c]	NOEL	subchronic
		oral	$1.2\cdot10^{-6}$	7.8 [d]	NOEL	subchronic
1,1,1–Trichloroethane	71–55–6	inhalation	$2.5\cdot10^{-4}$	380 [c]	NOEL	subchronic
		oral	$1.2\cdot10^{-7}$	n/a		
Trichloroethylene	79–01–6	inhalation	$7.4\cdot10^{-6}$	200 [c]	LOEL	chronic
		oral	$7.7\cdot10^{-9}$	100 [d]	LOEL	subchronic
Trichloromethane	67–66–3	inhalation	$5.1\cdot10^{-5}$	110 [c]	NOEL	subchronic
		oral	$6.5\cdot10^{-8}$	30 [d]	LOEL	chronic
Triethyl amine	121–44–8	inhalation	$3.0\cdot10^{-7}$	19.5 [c]	NOEL	subchronic
		oral	$4.7\cdot10^{-9}$	n/a		
Vinyl chloride	75–01–4	inhalation	$3.4\cdot10^{-6}$	5.6 [c]	NOEL	subchronic
		oral	$8.3\cdot10^{-10}$	0.13 [d]	NOEL	chronic
Xylenes	1330–20–7	inhalation	$1.7\cdot10^{-6}$	870 [c]	LOEL	chronic
		oral	$6.1\cdot10^{-9}$	150 [d]	LOEL	subchronic

[a] $F_{x,r,outdoor\rightarrow human}$: Intake fraction via uptake pathway r (inhalation or oral uptake) of compound x
[b] NOEL: No observed effect level; LOEL: Lowest observed effect level

Table A2 (continued): Data to calculate the characterisation factors for organic compounds

Substance	CAS #	Uptake path	Effects	Test animal	Damage factor [4] ($y \cdot case^{-1}$)	Literature
Acetaldehyde	75-07-0	inhalation	Degeneration of olfactory epithelium		0.67	[13]
		oral			0.67	
Acetone	67-64-1	inhalation			0.67	
		oral	Kidney, liver	Rat	0.67	[13]
Benzaldehyde	100-52-7	inhalation			0.67	
		oral	Stomach, kidney	Rat	0.67	[13]
Benzene	71-43-2	inhalation	Immunotoxicity		0.067	[14]
		oral			0.067	
n-Butanol	71-36-3	inhalation			0.067	
		oral	Ataxia and hypoactivity	Rat	0.067	[15]
2-Butoxy ethanol	111-76-2	inhalation	Blood		0.67	[13]
		oral	Haematological and liver effects	Rat	0.67	[13]
Butyl acetate	123-86-4	inhalation	Mucus irritation		0.067	[15]
		oral			0.067	
Carbon tetrachloride	56-23-5	inhalation	Liver		0.67	[14]
		oral	Hepatotoxicological effects	Rat	0.67	[14]
o-Cresol	95-48-7	inhalation			0.67	
		oral	Neurotoxicity	Rat	0.67	[13]
Cumene	98-82-8	inhalation	Kidney		0.67	[13]
		oral	Increased average kidney weight in female rats	Rat	0.67	[13]
1,1-Dichloroethane	75-34-3	inhalation	Haematology and biochemistry		0.67	[15]
		oral			0.67	
o-Dichlorobenzene	95-50-1	inhalation	(Histo)pathology		0.67	[14]
		oral	Tubular regeneration	Mouse	0.67	[14]
p-Dichlorobenzene	106-46-7	inhalation	Organ weight and biochemistry		0.67	[14]
		oral	Haematological effects, hepato- and nephrotoxicity	Dog	0.67	[14]
Dichloromethane	75-09-2	inhalation	Central nervous system, blood		0.67	[14]
		oral	Liver, central nervous system	Rat	0.67	[14,16]
Diethyl phthalate	84-66-2	inhalation			0.67	
		oral	Liver, testes	Rat	0.67	[14]
Ethyl acetate	141-78-6	inhalation			0.67	
		oral	Depressed body and organ weights	Rat	0.67	[17]
Ethyl benzene	100-41-4	inhalation	Liver and kidney		0.67	[14]
		oral	Liver, kidney, spleen and femur	Rat	0.67	[14,16]
Ethylene glycol	107-21-1	inhalation			0.67	
		oral	Kidney and liver	Rat	0.67	[15]
Formaldehyde	50-00-0	inhalation	Nasal, throat and eye irritation		0.067	[15]
		oral	Fore stomach	Rat	0.067	[15]
n-Hexane	110-54-3	inhalation	Neurotoxicity		0.67	[13]
		oral			0.67	
Methanol	67-56-1	inhalation			0.67	
		oral	Increased SAP and SGPT, decreased brain weight	Rat	0.67	[13]
Methyl ethyl ketone	78-93-3	inhalation	Teratogenity		6.7	[15]
		oral	Decreased fetal birth weight	Rat	0.67	[13]
Naphthalene	91-20-3	inhalation	Nasal effects		0.67	[13]
		oral	Decreased mean terminal body weight in males	Rat	0.67	[4]
Phenol	108-95-2	inhalation	Liver, lung, kidney		0.67	[14]
		oral	Developmental study	Rat	6.7	[13]
Phenyl chloride	108-90-7	inhalation	Central nervous system and other effects		0.67	[14]
		oral	Organ weights, histopathological effects	Dog	0.67	[14]
Propylene glycol monomethyl ether	107-98-2	inhalation	Mild reversible sedation		0.067	[13]
		oral			0.067	
Styrene	100-42-5	inhalation	Central nervous system		0.67	[14]
		oral	Decreased body weight	Rat	0.67	[14]
Tetrachloroethylene	127-18-4	inhalation	Renal failure		0.67	[14]
		oral	Liver	Rat	0.67	[14,16]
Toluene	108-88-3	inhalation	Central nervous system		0.67	[14]
		oral	Liver	Mouse	0.67	[14]
1,2,4-Trichlorobenzene	120-82-1	inhalation	Liver, kidney		0.67	[14]
		oral	Increased liver weight, histopatological effects	Rat	0.67	[14]
1,1,1-Trichloroethane	71-55-6	inhalation	Biochemistry		0.67	[15]
		oral			0.67	
Trichloroethylene	79-01-6	inhalation	Hepatotoxicity, central nervous system		0.67	[14]
		oral	Liver	Mouse	0.67	[14]
Trichloromethane	67-66-3	inhalation	Liver		0.67	[14]
		oral	Hepatotoxicological effects	Mouse	0.67	[14]
Triethyl amine	121-44-8	inhalation	Histopathology		0.67	[13]
		oral			0.67	
Vinyl chloride	75-01-4	inhalation	Testes		0.67	[14]
		oral	Liver	Rat	0.67	[14]
Xylenes	1330-20-7	inhalation	Neurotoxicity		0.67	[14]
		oral	Mild chronic nephropathy	Rat	0.67	[14]

Table A3: Fate factors of organic compounds (dimensionless)

Substance	CAS-nr	Crawlspace			First floor			Second floor		
		$F_{x,c,ii}$[a]	$F_{x,c,oi}$	$F_{x,c,oo}$	$F_{x,1,ii}$	$F_{x,1,oi}$	$F_{x,1,oo}$	$F_{x,2,ii}$	$F_{x,2,oi}$	$F_{x,2,oo}$
Acetaldehyde	75-07-0	$1.3\cdot10^{-5}$	$3.3\cdot10^{-7}$	$8.4\cdot10^{-9}$	$2.6\cdot10^{-2}$	$3.2\cdot10^{-7}$	$8.2\cdot10^{-9}$	$3.1\cdot10^{-2}$	$3.2\cdot10^{-7}$	$8.1\cdot10^{-9}$
Acetone	67-64-1	$1.3\cdot10^{-5}$	$1.0\cdot10^{-5}$	$6.8\cdot10^{-7}$	$2.6\cdot10^{-2}$	$9.7\cdot10^{-6}$	$6.6\cdot10^{-7}$	$3.1\cdot10^{-2}$	$9.7\cdot10^{-6}$	$6.6\cdot10^{-7}$
Benzaldehyde	100-52-7	$1.3\cdot10^{-5}$	$1.2\cdot10^{-6}$	$1.3\cdot10^{-6}$	$2.6\cdot10^{-2}$	$1.2\cdot10^{-6}$	$1.3\cdot10^{-6}$	$3.1\cdot10^{-2}$	$1.2\cdot10^{-6}$	$1.3\cdot10^{-6}$
Benzene	71-43-2	$1.3\cdot10^{-5}$	$1.2\cdot10^{-5}$	$2.3\cdot10^{-8}$	$2.6\cdot10^{-2}$	$1.2\cdot10^{-5}$	$2.2\cdot10^{-8}$	$3.1\cdot10^{-2}$	$1.2\cdot10^{-5}$	$2.2\cdot10^{-8}$
n-Butanol	71-36-3	$1.3\cdot10^{-5}$	$2.6\cdot10^{-6}$	$8.1\cdot10^{-7}$	$2.6\cdot10^{-2}$	$2.5\cdot10^{-6}$	$7.9\cdot10^{-7}$	$3.1\cdot10^{-2}$	$2.5\cdot10^{-6}$	$7.8\cdot10^{-7}$
2-Butoxy ethanol	111-76-2	$1.3\cdot10^{-5}$	$9.6\cdot10^{-7}$	$1.2\cdot10^{-6}$	$2.6\cdot10^{-2}$	$9.4\cdot10^{-7}$	$1.2\cdot10^{-6}$	$3.1\cdot10^{-2}$	$9.3\cdot10^{-7}$	$1.2\cdot10^{-6}$
Butyl acetate	123-86-4	$1.3\cdot10^{-5}$	$2.9\cdot10^{-6}$	$3.3\cdot10^{-8}$	$2.6\cdot10^{-2}$	$2.8\cdot10^{-6}$	$3.2\cdot10^{-8}$	$3.1\cdot10^{-2}$	$2.8\cdot10^{-6}$	$3.2\cdot10^{-8}$
Carbon tetrachloride	56-23-5	$1.3\cdot10^{-5}$	$5.3\cdot10^{-4}$	$2.1\cdot10^{-7}$	$2.6\cdot10^{-2}$	$5.2\cdot10^{-4}$	$2.0\cdot10^{-7}$	$3.1\cdot10^{-2}$	$5.1\cdot10^{-4}$	$2.0\cdot10^{-7}$
o-Cresol	95-48-7	$1.3\cdot10^{-5}$	$1.9\cdot10^{-7}$	$4.8\cdot10^{-7}$	$2.6\cdot10^{-2}$	$1.9\cdot10^{-7}$	$4.7\cdot10^{-7}$	$3.1\cdot10^{-2}$	$1.8\cdot10^{-7}$	$4.7\cdot10^{-7}$
Cumene	98-82-8	$1.3\cdot10^{-5}$	$1.1\cdot10^{-6}$	$7.2\cdot10^{-9}$	$2.6\cdot10^{-2}$	$1.1\cdot10^{-6}$	$7.0\cdot10^{-9}$	$3.1\cdot10^{-2}$	$1.1\cdot10^{-6}$	$6.9\cdot10^{-9}$
1,1-Dichloroethane	75-34-3	$1.3\cdot10^{-5}$	$3.3\cdot10^{-5}$	$3.0\cdot10^{-8}$	$2.6\cdot10^{-2}$	$3.2\cdot10^{-5}$	$2.9\cdot10^{-8}$	$3.1\cdot10^{-2}$	$3.2\cdot10^{-5}$	$2.9\cdot10^{-8}$
o-Dichlorobenzene	95-50-1	$1.3\cdot10^{-5}$	$2.2\cdot10^{-5}$	$4.4\cdot10^{-7}$	$2.6\cdot10^{-2}$	$2.1\cdot10^{-5}$	$4.3\cdot10^{-7}$	$3.1\cdot10^{-2}$	$2.1\cdot10^{-5}$	$4.3\cdot10^{-7}$
p-Dichlorobenzene	106-46-7	$1.3\cdot10^{-5}$	$2.7\cdot10^{-5}$	$2.1\cdot10^{-7}$	$2.6\cdot10^{-2}$	$2.6\cdot10^{-5}$	$2.1\cdot10^{-7}$	$3.1\cdot10^{-2}$	$2.6\cdot10^{-5}$	$2.1\cdot10^{-7}$
Dichloromethane	75-09-2	$1.3\cdot10^{-5}$	$3.4\cdot10^{-5}$	$4.3\cdot10^{-8}$	$2.6\cdot10^{-2}$	$3.3\cdot10^{-5}$	$4.2\cdot10^{-8}$	$3.1\cdot10^{-2}$	$3.3\cdot10^{-5}$	$4.2\cdot10^{-8}$
Diethyl phthalate	84-66-2	$1.3\cdot10^{-5}$	$2.6\cdot10^{-6}$	$3.0\cdot10^{-5}$	$2.6\cdot10^{-2}$	$2.5\cdot10^{-6}$	$2.9\cdot10^{-5}$	$3.1\cdot10^{-2}$	$2.5\cdot10^{-6}$	$2.9\cdot10^{-5}$
Ethyl acetate	141-78-6	$1.3\cdot10^{-5}$	$2.8\cdot10^{-6}$	$5.8\cdot10^{-8}$	$2.6\cdot10^{-2}$	$2.8\cdot10^{-6}$	$5.7\cdot10^{-8}$	$3.1\cdot10^{-2}$	$2.7\cdot10^{-6}$	$5.7\cdot10^{-8}$
Ethyl benzene	100-41-4	$1.3\cdot10^{-5}$	$3.0\cdot10^{-6}$	$9.2\cdot10^{-9}$	$2.6\cdot10^{-2}$	$2.9\cdot10^{-6}$	$9.0\cdot10^{-9}$	$3.1\cdot10^{-2}$	$2.9\cdot10^{-6}$	$8.9\cdot10^{-9}$
Ethylene glycol	107-21-1	$1.3\cdot10^{-5}$	$4.0\cdot10^{-7}$	$1.1\cdot10^{-5}$	$2.6\cdot10^{-2}$	$3.9\cdot10^{-7}$	$1.1\cdot10^{-5}$	$3.1\cdot10^{-2}$	$3.9\cdot10^{-7}$	$1.1\cdot10^{-5}$
Formaldehyde	50-00-0	$1.3\cdot10^{-5}$	$1.4\cdot10^{-6}$	$9.2\cdot10^{-6}$	$2.6\cdot10^{-2}$	$1.4\cdot10^{-6}$	$9.0\cdot10^{-6}$	$3.1\cdot10^{-2}$	$1.4\cdot10^{-6}$	$8.9\cdot10^{-6}$
n-Hexane	110-54-3	$1.3\cdot10^{-5}$	$1.1\cdot10^{-6}$	$8.3\cdot10^{-10}$	$2.6\cdot10^{-2}$	$1.1\cdot10^{-6}$	$8.0\cdot10^{-10}$	$3.1\cdot10^{-2}$	$1.1\cdot10^{-6}$	$8.0\cdot10^{-10}$
Methanol	67-56-1	$1.3\cdot10^{-5}$	$6.9\cdot10^{-6}$	$3.8\cdot10^{-6}$	$2.6\cdot10^{-2}$	$6.7\cdot10^{-6}$	$3.7\cdot10^{-6}$	$3.1\cdot10^{-2}$	$6.7\cdot10^{-6}$	$3.7\cdot10^{-6}$
Methyl ethyl ketone	78-93-3	$1.3\cdot10^{-5}$	$5.6\cdot10^{-6}$	$3.5\cdot10^{-7}$	$2.6\cdot10^{-2}$	$5.4\cdot10^{-6}$	$3.4\cdot10^{-7}$	$3.1\cdot10^{-2}$	$5.4\cdot10^{-6}$	$3.4\cdot10^{-7}$
Naphthalene	91-20-3	$1.3\cdot10^{-5}$	$9.8\cdot10^{-7}$	$7.8\cdot10^{-8}$	$2.6\cdot10^{-2}$	$9.5\cdot10^{-7}$	$7.6\cdot10^{-8}$	$3.1\cdot10^{-2}$	$9.5\cdot10^{-7}$	$7.6\cdot10^{-8}$
Phenol	108-95-2	$1.3\cdot10^{-5}$	$7.2\cdot10^{-7}$	$3.7\cdot10^{-6}$	$2.6\cdot10^{-2}$	$7.0\cdot10^{-7}$	$3.6\cdot10^{-6}$	$3.1\cdot10^{-2}$	$7.0\cdot10^{-7}$	$3.6\cdot10^{-6}$
Phenyl chloride	108-90-7	$1.3\cdot10^{-5}$	$1.6\cdot10^{-5}$	$5.4\cdot10^{-8}$	$2.6\cdot10^{-2}$	$1.5\cdot10^{-5}$	$5.3\cdot10^{-8}$	$3.1\cdot10^{-2}$	$1.5\cdot10^{-5}$	$5.3\cdot10^{-8}$
Propylene glycol monomethyl ether	107-98-2	$1.3\cdot10^{-5}$	$1.3\cdot10^{-6}$	$2.9\cdot10^{-6}$	$2.6\cdot10^{-2}$	$1.2\cdot10^{-6}$	$2.8\cdot10^{-6}$	$3.1\cdot10^{-2}$	$1.2\cdot10^{-6}$	$2.8\cdot10^{-6}$
Styrene	100-42-5	$1.3\cdot10^{-5}$	$4.9\cdot10^{-7}$	$3.5\cdot10^{-9}$	$2.6\cdot10^{-2}$	$4.8\cdot10^{-7}$	$3.4\cdot10^{-9}$	$3.1\cdot10^{-2}$	$4.7\cdot10^{-7}$	$3.4\cdot10^{-9}$
Tetrachloroethylene	127-18-4	$1.3\cdot10^{-5}$	$5.5\cdot10^{-5}$	$3.5\cdot10^{-8}$	$2.6\cdot10^{-2}$	$5.4\cdot10^{-5}$	$3.4\cdot10^{-8}$	$3.1\cdot10^{-2}$	$5.4\cdot10^{-5}$	$3.4\cdot10^{-8}$
Toluene	108-88-3	$1.3\cdot10^{-5}$	$3.6\cdot10^{-6}$	$4.6\cdot10^{-9}$	$2.6\cdot10^{-2}$	$3.5\cdot10^{-6}$	$4.5\cdot10^{-9}$	$3.1\cdot10^{-2}$	$3.5\cdot10^{-6}$	$4.5\cdot10^{-9}$
1,2,4-Trichlorobenzene	120-82-1	$1.3\cdot10^{-5}$	$2.0\cdot10^{-5}$	$1.2\cdot10^{-6}$	$2.6\cdot10^{-2}$	$1.9\cdot10^{-5}$	$1.1\cdot10^{-6}$	$3.1\cdot10^{-2}$	$1.9\cdot10^{-5}$	$1.1\cdot10^{-6}$
1,1,1-Trichloroethane	71-55-6	$1.3\cdot10^{-5}$	$2.5\cdot10^{-4}$	$1.2\cdot10^{-7}$	$2.6\cdot10^{-2}$	$2.4\cdot10^{-4}$	$1.1\cdot10^{-7}$	$3.1\cdot10^{-2}$	$2.4\cdot10^{-4}$	$1.1\cdot10^{-7}$
Trichloroethylene	79-01-6	$1.3\cdot10^{-5}$	$7.4\cdot10^{-6}$	$7.7\cdot10^{-9}$	$2.6\cdot10^{-2}$	$7.3\cdot10^{-6}$	$7.5\cdot10^{-9}$	$3.1\cdot10^{-2}$	$7.2\cdot10^{-6}$	$7.4\cdot10^{-9}$
Trichloromethane	67-66-3	$1.3\cdot10^{-5}$	$5.1\cdot10^{-5}$	$6.5\cdot10^{-8}$	$2.6\cdot10^{-2}$	$4.9\cdot10^{-5}$	$6.3\cdot10^{-8}$	$3.1\cdot10^{-2}$	$4.9\cdot10^{-5}$	$6.3\cdot10^{-8}$
Triethyl amine	121-44-8	$1.3\cdot10^{-5}$	$3.0\cdot10^{-7}$	$4.7\cdot10^{-9}$	$2.6\cdot10^{-2}$	$2.9\cdot10^{-7}$	$4.6\cdot10^{-9}$	$3.1\cdot10^{-2}$	$2.9\cdot10^{-7}$	$4.5\cdot10^{-9}$
Vinyl chloride	75-01-4	$1.3\cdot10^{-5}$	$3.4\cdot10^{-6}$	$8.3\cdot10^{-10}$	$2.6\cdot10^{-2}$	$3.3\cdot10^{-6}$	$8.1\cdot10^{-10}$	$3.1\cdot10^{-2}$	$3.3\cdot10^{-6}$	$8.0\cdot10^{-10}$
Xylenes	1330-20-7	$1.3\cdot10^{-5}$	$1.7\cdot10^{-6}$	$6.1\cdot10^{-9}$	$2.6\cdot10^{-2}$	$1.7\cdot10^{-6}$	$5.9\cdot10^{-9}$	$3.1\cdot10^{-2}$	$1.6\cdot10^{-6}$	$5.9\cdot10^{-9}$

[a] $F_{x,a,r}$: Fate factor of compound *x* emitted to compartment *a* (crawl space, first floor or second floor) causing human exposure via intake pathway *r* (indoor inhalation, outdoor inhalation or outdoor oral uptake)

Table A4: Effect factors of organic compounds (cases·kg^{-1})

Substance	CAS-nr	$E_{x,c,i}$[a]	$E_{x,c,o}$	$E_{x,nc,i}$	$E_{x,nc,o}$
Acetaldehyde	75-07-0	$3.2\cdot10^{-3}$	$2.2\cdot10^{-3}$	$4.2\cdot10^{-2}$	$5.6\cdot10^{-2}$
Acetone	67-64-1	n/a	n/a	$2.1\cdot10^{-3}$	$2.8\cdot10^{-3}$
Benzaldehyde	100-52-7	n/a	n/a	$1.5\cdot10^{-3}$	$2.0\cdot10^{-3}$
Benzene	71-43-2	$8.8\cdot10^{-3}$	$8.1\cdot10^{-3}$	$2.3\cdot10^{-1}$	$3.0\cdot10^{-1}$
n-Butanol	71-36-3	n/a	n/a	$1.7\cdot10^{-3}$	$2.3\cdot10^{-3}$
2-Butoxy ethanol	111-76-2	n/a	n/a	$1.3\cdot10^{-2}$	$5.2\cdot10^{-3}$
Butyl acetate	123-86-4	n/a	n/a	$2.0\cdot10^{-2}$	$2.7\cdot10^{-2}$
Carbon tetrachloride	56-23-5	$2.2\cdot10^{-2}$	$3.6\cdot10^{-2}$	$2.8\cdot10^{-2}$	$2.8\cdot10^{-1}$
o-Cresol	95-48-7	n/a	n/a	$4.3\cdot10^{-3}$	$5.7\cdot10^{-3}$
Cumene	98-82-8	n/a	n/a	$8.4\cdot10^{-4}$	$2.6\cdot10^{-3}$
1,1-Dichloroethane	75-34-3	n/a	n/a	$1.0\cdot10^{-3}$	$1.3\cdot10^{-3}$
o-Dichlorobenzene	95-50-1	n/a	n/a	$6.1\cdot10^{-3}$	$5.9\cdot10^{-3}$
p-Dichlorobenzene	106-46-7	n/a	n/a	$2.7\cdot10^{-3}$	$1.0\cdot10^{-2}$
Dichloromethane	75-09-2	$6.9\cdot10^{-4}$	$2.1\cdot10^{-3}$	$6.1\cdot10^{-2}$	$2.4\cdot10^{-2}$
Diethyl phthalate	84-66-2	n/a	n/a	$2.1\cdot10^{-3}$	$2.8\cdot10^{-3}$
Ethyl acetate	141-78-6	n/a	n/a	$2.4\cdot10^{-4}$	$3.2\cdot10^{-4}$
Ethyl benzene	100-41-4	n/a	n/a	$4.7\cdot10^{-3}$	$2.9\cdot10^{-3}$
Ethylene glycol	107-21-1	n/a	n/a	$2.7\cdot10^{-3}$	$3.6\cdot10^{-3}$
Formaldehyde	50-00-0	$1.9\cdot10^{-2}$	$1.3\cdot10^{-2}$	3.0	$9.5\cdot10^{-3}$
n-Hexane	110-54-3	n/a	n/a	$1.3\cdot10^{-2}$	$1.8\cdot10^{-2}$
Methanol	67-56-1	n/a	n/a	$4.3\cdot10^{-4}$	$5.7\cdot10^{-4}$
Methyl ethyl ketone	78-93-3	n/a	n/a	$2.1\cdot10^{-4}$	$1.6\cdot10^{-4}$
Naphthalene	91-20-3	n/a	n/a	$1.0\cdot10^{-1}$	$8.8\cdot10^{-3}$
Phenol	108-95-2	n/a	n/a	$1.8\cdot10^{-2}$	$1.3\cdot10^{-3}$
Phenyl chloride	108-90-7	n/a	n/a	$5.7\cdot10^{-3}$	$5.3\cdot10^{-3}$
Propylene glycol monomethyl ether	107-98-2	n/a	n/a	$5.5\cdot10^{-4}$	$7.4\cdot10^{-4}$
Styrene	100-42-5	$8.4\cdot10^{-4}$	$5.6\cdot10^{-4}$	$3.7\cdot10^{-2}$	$1.2\cdot10^{-2}$
Tetrachloroethylene	127-18-4	$8.5\cdot10^{-4}$	n/a	$3.9\cdot10^{-2}$	$4.4\cdot10^{-2}$
Toluene	108-88-3	n/a	n/a	$8.2\cdot10^{-3}$	$1.2\cdot10^{-2}$
1,2,4-Trichlorobenzene	120-82-1	n/a	n/a	$9.1\cdot10^{-2}$	$3.6\cdot10^{-2}$
1,1,1-Trichloroethane	71-55-6	n/a	n/a	$9.6\cdot10^{-4}$	$1.3\cdot10^{-3}$
Trichloroethylene	79-01-6	$6.3\cdot10^{-4}$	n/a	$4.9\cdot10^{-3}$	$2.5\cdot10^{-3}$
Trichloromethane	67-66-3	$3.4\cdot10^{-2}$	$1.7\cdot10^{-3}$	$3.3\cdot10^{-3}$	$4.5\cdot10^{-2}$
Triethyl amine	121-44-8	n/a	n/a	$1.9\cdot10^{-2}$	$2.5\cdot10^{-2}$
Vinyl chloride	75-01-4	$1.5\cdot10^{-3}$	$9.8\cdot10^{-4}$	$6.5\cdot10^{-2}$	1.1
Xylenes	1330-20-7	n/a	n/a	$1.1\cdot10^{-3}$	$1.0\cdot10^{-2}$

[a] $E_{x,k,r}$: Effect factor of compound *x* taken up via intake pathway *r* (inhalation or oral uptake) causing health damage category *k* (carcinogenic effects or non-carcinogenic effects)

Table A5: Damage factors of organic compounds (y·case⁻¹) [4,5]

Substance	CAS-nr	$D_{x,c,i}$ [a]	$D_{x,c,o}$	$D_{x,nc,i}$	$D_{x,nc,o}$
Acetaldehyde	75-07-0	13.1	13.1	0.67	0.67
Acetone	67-64-1	n/a	n/a	0.67	0.67
Benzaldehyde	100-52-7	n/a	n/a	0.67	0.67
Benzene	71-43-2	16.5	16.5	0.067	0.067
n-Butanol	71-36-3	n/a	n/a	0.067	0.067
2-Butoxy ethanol	111-76-2	n/a	n/a	0.67	0.67
Butyl acetate	123-86-4	n/a	n/a	0.067	0.067
Carbon tetrachloride	56-23-5	16.2	16.2	0.67	0.67
o-Cresol	95-48-7	n/a	n/a	0.67	0.67
Cumene	98-82-8	n/a	n/a	0.67	0.67
1,1-Dichloroethane	75-34-3	n/a	n/a	0.67	0.67
o-Dichlorobenzene	95-50-1	n/a	n/a	0.67	0.67
p-Dichlorobenzene	106-46-7	n/a	n/a	0.67	0.67
Dichloromethane	75-09-2	13.1	13.1	0.67	0.67
Diethyl phthalate	84-66-2	n/a	n/a	0.67	0.67
Ethyl acetate	141-78-6	n/a	n/a	0.67	0.67
Ethyl benzene	100-41-4	n/a	n/a	0.67	0.67
Ethylene glycol	107-21-1	n/a	n/a	0.67	0.67
Formaldehyde	50-00-0	12.5	13.1	0.067	0.067
n-Hexane	110-54-3	n/a	n/a	0.67	0.67
Methanol	67-56-1	n/a	n/a	0.67	0.67
Methyl ethyl ketone	78-93-3	n/a	n/a	6.7	0.67
Naphthalene	91-20-3	n/a	n/a	0.67	0.67
Phenol	108-95-2	n/a	n/a	0.67	6.7
Phenyl chloride	108-90-7	n/a	n/a	0.67	0.67
Propylene glycol monomethyl ether	107-98-2	n/a	n/a	0.067	0.067
Styrene	100-42-5	13.1	13.1	0.67	0.67
Tetrachloroethylene	127-18-4	13.1	13.1	0.67	0.67
Toluene	108-88-3	n/a	n/a	0.67	0.67
1,2,4-Trichlorobenzene	120-82-1	n/a	n/a	0.67	0.67
1,1,1-Trichloroethane	71-55-6	n/a	n/a	0.67	0.67
Trichloroethylene	79-01-6	13.1	13.1	0.67	0.67
Trichloromethane	67-66-3	13.1	13.1	0.67	0.67
Triethyl amine	121-44-8	n/a	n/a	0.67	0.67
Vinyl chloride	75-01-4	16.2	16.2	0.67	0.67
Xylenes	1330-20-7	n/a	n/a	0.67	0.67

[a] $D_{x,k,r}$: Damage factor of compound *x* taken up via intake pathway *r* (inhalation or oral uptake) causing health damage category *k* (carcinogenic effects or non-carcinogenic effects)

Table A6: Characterisation factors of organic compounds for respiratory effects, climate change and ozone layer depletion (DALY·kg⁻¹)

Substance	CAS-nr	Respiratory effects	Climate change	Ozone layer depletion
Acetaldehyde	75-07-0	$1.4 \cdot 10^{-6}$	0	0
Acetone	67-64-1	$2.0 \cdot 10^{-7}$	0	0
Benzaldehyde	100-52-7	$1.4 \cdot 10^{-6}$	0	0
Benzene	71-43-2	$4.7 \cdot 10^{-7}$	0	0
n-Butanol	71-36-3	$1.4 \cdot 10^{-6}$	0	0
2-Butoxy ethanol	111-76-2	$9.4 \cdot 10^{-7}$	0	0
Butyl acetate	123-86-4	$5.2 \cdot 10^{-7}$	0	0
Carbon tetrachloride	56-23-5	$3.5 \cdot 10^{-7}$	$-2.6 \cdot 10^{-4}$	$1.3 \cdot 10^{-3}$
o-Cresol	95-48-7	$2.1 \cdot 10^{-6}$	0	0
Cumene	98-82-8	$1.1 \cdot 10^{-6}$	0	0
1,1-Dichloroethane	75-34-3	$3.5 \cdot 10^{-7}$	0	0
o-Dichlorobenzene	95-50-1	$2.1 \cdot 10^{-6}$	0	0
p-Dichlorobenzene	106-46-7	$2.1 \cdot 10^{-6}$	0	0
Dichloromethane	75-09-2	$1.5 \cdot 10^{-7}$	$1.9 \cdot 10^{-6}$	0
Diethyl phthalate	84-66-2	$2.1 \cdot 10^{-6}$	0	0
Ethyl acetate	141-78-6	$4.6 \cdot 10^{-7}$	0	0
Ethyl benzene	100-41-4	$1.5 \cdot 10^{-6}$	0	0
Ethylene glycol	107-21-1	$8.3 \cdot 10^{-7}$	0	0
Formaldehyde	50-00-0	$1.1 \cdot 10^{-6}$	0	0
n-Hexane	110-54-3	$1.0 \cdot 10^{-6}$	0	0
Methanol	67-56-1	$2.8 \cdot 10^{-7}$	0	0
Methyl ethyl ketone	78-93-3	$8.1 \cdot 10^{-7}$	0	0
Naphthalene	91-20-3	$2.1 \cdot 10^{-6}$	0	0
Phenol	108-95-2	$2.1 \cdot 10^{-6}$	0	0
Phenyl chloride	108-90-7	$2.1 \cdot 10^{-6}$	0	0
Propylene glycol monomethyl ether	107-98-2	$7.9 \cdot 10^{-7}$	0	0
Styrene	100-42-5	$2.1 \cdot 10^{-6}$	0	0
Tetrachloroethylene	127-18-4	$6.2 \cdot 10^{-8}$	0	0
Toluene	108-88-3	$1.4 \cdot 10^{-6}$	0	0
1,2,4-Trichlorobenzene	120-82-1	$2.1 \cdot 10^{-6}$	0	0
1,1,1-Trichloroethane	71-55-6	$2.0 \cdot 10^{-8}$	$-4.3 \cdot 10^{-5}$	$1.3 \cdot 10^{-4}$
Trichloroethylene	79-01-6	$7.0 \cdot 10^{-7}$	0	0
Trichloromethane	67-66-3	$4.9 \cdot 10^{-8}$	$8.3 \cdot 10^{-7}$	0
Triethyl amine	121-44-8	0	0	0
Vinyl chloride	75-01-4	$2.1 \cdot 10^{-6}$	0	0
Xylenes	1330-20-7	$2.4 \cdot 10^{-6}$	0	0

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