FRAMEWORK FOR INTEGRATING INDOOR AIR QUALITY IMPACTS INTO LIFE CYCLE ASSESSMENTS OF BUILDINGS AND BUILDING RELATED PRODUCTS

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ABSTRACT

Products used during construction and operation of a building can contribute to Indoor Air Quality (IAQ) problems that affect occupants' well-being. However, IAQ is conventionally not addressed in the life cycle assessments (LCAs) of buildings and building related products even though IAQ leads to one of the areas of protection under LCA - human health impacts. In this study, we proposed an overall framework for integrating IAQ into LCA using the standard steps of LCA. The framework focused on IAQ and LCA modeling from two categories of building related products: i) passive products that realize their function through initial installation and have long-term decayed emissions, and ii) active equipment that realize their function and cause emissions through daily operation. Dynamic and static life cycle inventory modeling approaches were proposed for passive products and active equipment, respectively. An indoor intake fraction equation and USEtox model effect factors were incorporated into the life cycle impact assessment. Three hypothetical examples were presented to illustrate the calculation procedure of the framework. We concluded that it was feasible to integrate IAQ into building related LCA studies. Development of IAQ related impact assessment methodologies can improve upon the limitations of this study. Further studies need to be carried out to compare the health impacts from IAQ related sources to other life cycle stages of building related products.

KEYWORDS

building related products, indoor air quality, life cycle assessment

1. INTRODUCTION

Life cycle assessment (LCA) is a tool to assess the potential environmental impacts along a product's life cycle: from raw material extraction to manufacturing, and use to end of life management. As a comprehensive tool that avoids burden shifting, LCA has gained extensive support from the building community (AIA, 2010; Connor et al., 2012; USGBC, 2014).

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LCA can be used as an early-stage eco-design tool to assess and compare different design choices in order to achieve the ultimate goal of sustainable buildings. A typical building LCA includes the upstream manufacturing, on-site construction, operation, and end of life stages (Figure 1). Previous studies mainly focused on the manufacturing stage of building materials (Lazzarin et al., 2008; Thiel et al., 2013), or on the impacts from operational stages, of which energy consumption was the topic predominantly assessed (Gong et al., 2012; Rossi et al., 2012; Zabalza et al., 2013). The consideration of indoor air quality (IAQ) during operational stage (dashed line box in Figure 1) is conceptually important because poor IAQ causes sick building syndrome and leaves long-term effects on human health. This impact should be modelled in LCA as it is one of the areas of protection of LCA. Some advances were made in developing life cycle impact assessment (LCIA) methods for IAQ, such as the development of the characterization factors, damage scores (Meijer et al., 2005a, 2005b), and the indoor intake fraction (Hellweg et al., 2009; Wenger et al., 2012). Nevertheless, there is limited literature and a lack of information on modeling the IAQ in the operational stage of a building LCA, perhaps due to a lack of practical guideline/framework for integrating IAQ into building and building related products LCA.

Thus, the objective of this study was to propose such a guideline/framework, with a focus on IAQ associated with building related products. IAQ issues may be different for different types of buildings (e.g., supermarket, hospital, and residence). The framework was developed specifically for residential buildings because people spend a large proportion of their time (69% in the US) in their homes (Klepeis et al., 2001). The framework takes a modular approach, where the framework can be applied to product-level LCA first and then integrated into the whole-building LCA studies (Figure 1). In this paper, we describe the framework and provide example applications.

Figure 1: Application of the proposed framework to the whole-building LCA (WBLCA)
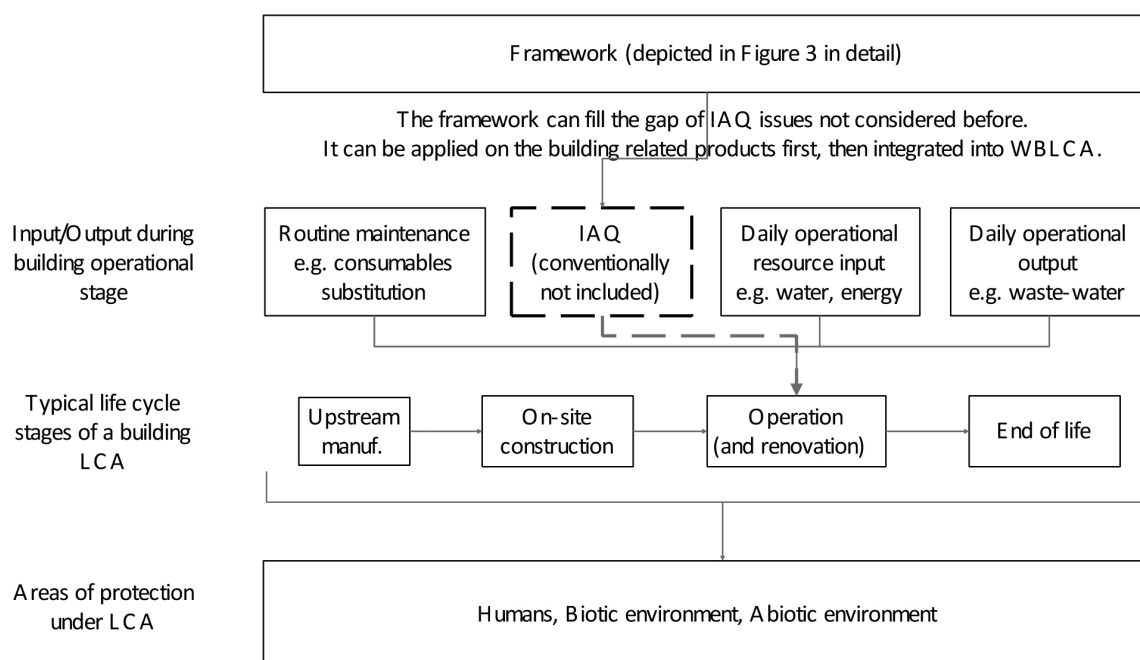
2. SCOPE OF THE PROPOSED FRAMEWORK

IAQ can be affected by different sources and operating conditions. We identified two conditions (boxes I and II in Figure 2) and three sources (boxes 1, 2, and 3 in Figure 2) that affect IAQ in residential buildings. Climate conditions include temperature, humidity, and wind that can affect the IAQ primarily via open windows. Climate conditions were not included in the framework for simplicity. The building use pattern includes conditions related to building occupancy numbers, residence times, and mechanical and natural ventilation rates. The incorporation of building use pattern into the numerical building parameters for IAQ modeling is explained in sections 3.2 and 3.3 and via the modeling of different scenarios (e.g., increased ventilation) in section 4.

Outside sources (e.g., soil radon, outdoor air pollution) are site dependent and not the focus of the framework. Other sources, such as the presence of human beings and their behavior (e.g., adoption of pets, foot traffic frequency), as well as accidental emissions from damaged materials (e.g., asbestos), also contribute to IAQ, but they were also left out of the scope of the framework for simplicity. The third type of source that affects IAQ is building related products. Since the goal of the proposed framework was to integrate IAQ from building related products, this source is described in greater detail and includes three sub-categories: the stationary and passive products, the active equipment, and the small pieces of active products (Figure 2).

Figure 2: Factors affecting IAQ during building occupancy (solid lines are within the scope of the proposed framework)
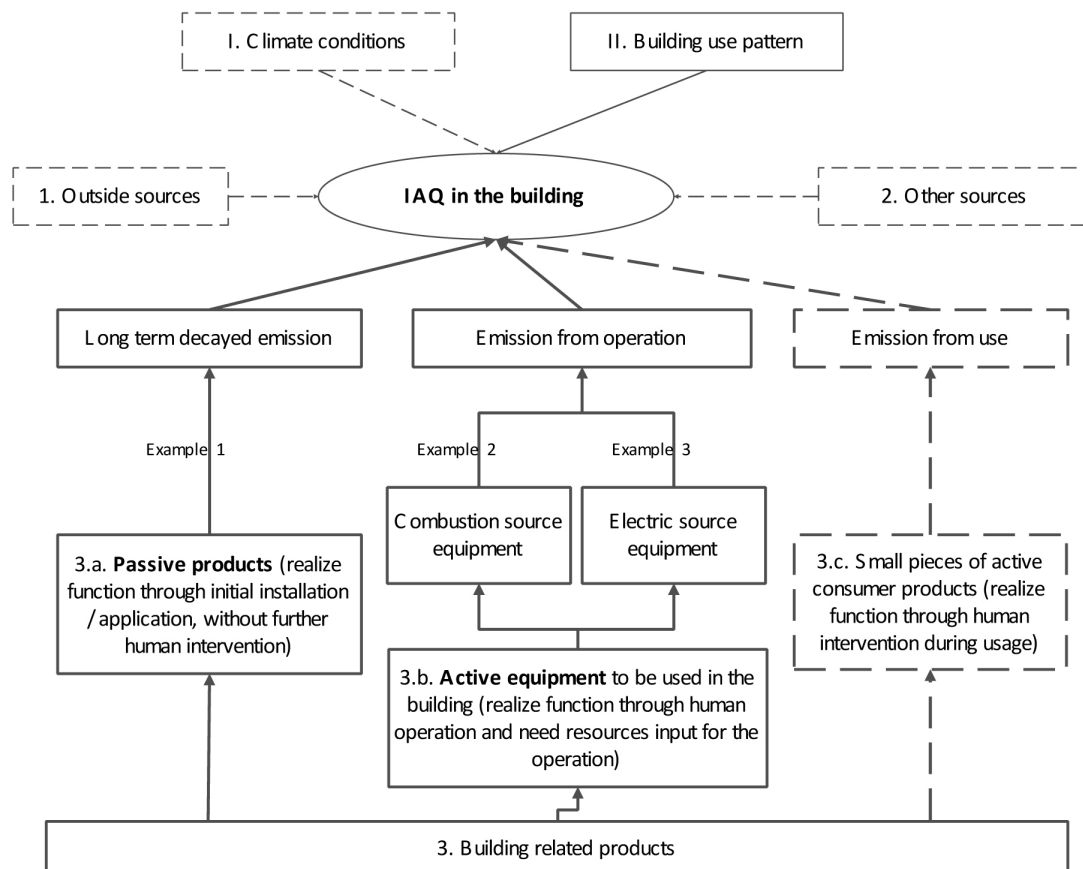
The passive product category (box 3.a in Figure 2) is generally stationary and includes fixed building products (e.g., concrete, plaster, marbles, insulation materials), furniture (e.g., floor covering products, wood-based products, polymeric building products), and finishing products (e.g., binders, paints, coatings, polishes). Passive products cause a wide range of indoor air emissions, such as VOCs, heavy metal, and radioactive emissions (e.g., radon). They are named "passive" as they realize their function after initial installation without further human intervention. After installation, passive products have emissions for a long term. However, the rate of emissions decays with time.

The active equipment category (box 3.b in Figure 2) refers to the equipment that is not part of the building but is operated within it to meet residential needs. It is named "active" as this type of equipment realizes its function through human operation and needs resource inputs to operate. This building related product category can be further sub-grouped based on the resource input as combustion source equipment (e.g., cooking stoves, ovens, furnaces, fireplaces) and electric source equipment (e.g., computers, printers, vacuum cleaners, washer & dryer, electric space heaters). Emissions from active equipment are periodic and occur during the operation of the equipment.

The third category of building related products is the small pieces of active products (box 3.c in Figure 2). This category refers to small pieces of consumer products used within the building (e.g., personal care products, cleaning products). These products are named as "active" as they realize their function through use or application. Unlike active equipment as common practice during building occupancy, the occurrence of these products is more subjective to individual behavior (e.g., whether or not to smoke). For this reason, they are not within the scope of the proposed framework.

3. STEPS OF THE IAQ-LCA FRAMEWORK

The integration of IAQ modeling into the LCA steps is shown in Figure 3. Dashed lines indicate parts not addressed within the scope of this study. Passive product specific modeling is shown in dark gray boxes and the active equipment specific modeling is shown in light gray boxes. Boxes without background color apply to both the passive product and active equipment modeling.

3.1 Goal and Scope

As in any LCA study, the first step of the framework is to determine the goal and scope. The goal of the study affects the scope of the study and the targeting audiences, which in turn would directly affect the data requirement in the inventory stage. For example, if the goal is a preliminary/screening study for certain building products with IAQ incorporated, then the inventory data may be obtained from secondary sources. If the goal is to communicate results to external stakeholders and publicize (e.g., Environmental Product Declaration (EPD)), then higher quality primary data is preferred.

An important task in the goal and scope phase is to define the functional unit. For building related products, the functional unit should be defined in a way that can be further integrated consistently into the whole-building LCA (modular approach). When determining how long the products/equipment would serve its functions, different ways for choosing time period were proposed in prior studies (Collinge, 2013; Verbeeck & Hens, 2010).

In this study two separate approaches are proposed for defining the functional unit for passive products and for active equipment. For passive products the time period for the

Figure 3: Overall framework to integrate IAQ into LCA
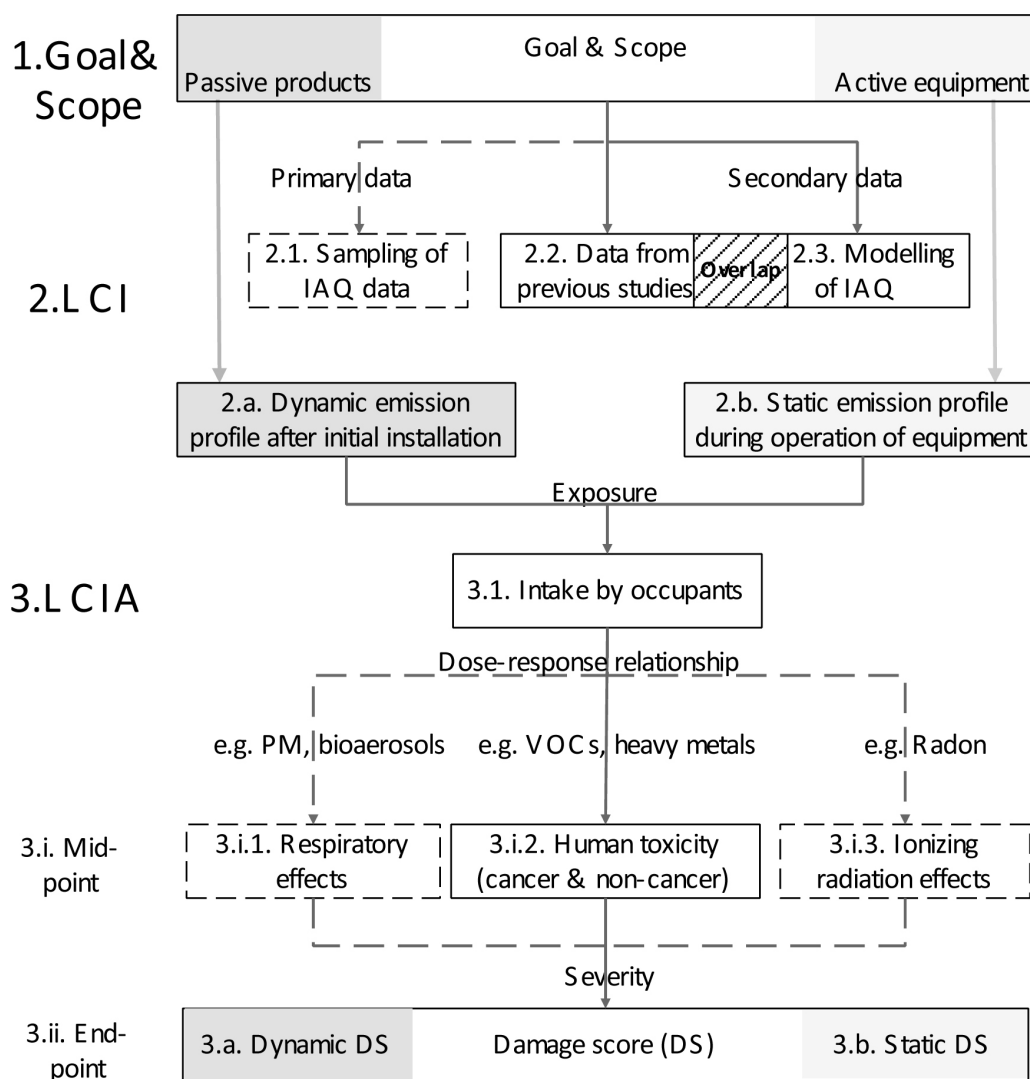
functional unit can be set equal to the estimated service life of the product. Later on, if integrated into the whole-building LCA and the same product is to be replaced, the total service life can be obtained by multiplying the single service life by the replacement times (i.e., service years of the building divided by the estimated service years of the product). The service life of the product is recommended over building service years because technology may change over the lifetime of the building resulting in availability of other types of products fulfilling the same function. Therefore, it may not be possible to replace the product with the exact same one over the building service time.

For the active equipment, the period recommended is for one year. Later on, if integrated into the whole-building LCA, one can multiply the one year emissions (and consequent impacts) with the potential service years of the equipment, which varies largely depending on the type of the equipment. For example, personal electric equipment may serve a couple of years to a decade depending on user behavior and other technology factors.

3.2 Life Cycle Inventory

The second step of the framework is the build-up of life cycle inventory (LCI) related with IAQ. This can be done through sampling in the building or chamber testing (box 2.1 in Figure 3), collection of data from previous studies (box 2.2 in Figure 3), or modelling of IAQ (box 2.3 in Figure 3). An overlap box is included between box 2.2 and box 2.3 in Figure 3 to indicate that data from previous studies often need to be fitted in mass balance models with the studied systems' own parameters (e.g., volume, air change rate). Collection of secondary data may be possible in some cases because previous studies have already been carried out regarding IAQ on building material/products (Sack et al., 1992; Won et al., 2003, 2005) and operation of equipment (Bakó-Biró et al., 2004; Destaillats et al., 2008).

The inventory can be modeled as a dynamic emission profile (box 2.a in Figure 3) for passive products or as a static emission profile (box 2.b in Figure 3) for active equipment. The word dynamic refers to the time based decay of the emission rate in passive products. Some examples of decay models are the first order exponential decay, the double-exponential decay, and the delayed first-order decay (Brown, 2009). The word static refers to the constant rate of emissions from the active equipment during the operation. Both profiles can be modeled by conducting a mass balance of the contaminants in the indoor environment (Kumar & Vempati, 2013). For one-compartment, the mass balance equation can be written as:

Mass of chemical$_{(x)}$ indoor = mass of chemical$_{(x)}$ entering indoor + mass of chemical$_{(x)}$ emitted indoor (source) – mass of chemical$_{(x)}$ leaving indoor – mass of chemical$_{(x)}$ removed indoor (removal)

$$\text{Equation (1)}$$

The mathematical formula and assumptions and implementation of equation (1) is elaborated in sections S.1.1 and S.1.2 of the Supplementary Information (SI). For the dynamic emission profile, the source term (S) is replaced with a first order decay model. Then, the mass balance equation is solved for the instantaneous concentration $C_{(t,x)}$, which is integrated over a period of time, t_1 to t_2, to obtain the cumulative concentration over that time interval, $C_{(t1-t2,x)}$ [kg m^{-3}]. The cumulative concentrations from different time periods constitute the dynamic LCI, which is then used to estimate the health impacts for different time periods in the LCIA stage using equation (4.i) and (4.ii).

For the static emission profile from active equipment, the source term (S) is a constant due to constant emission rate from the equipment during its operation. The mass balance equation is solved for the steady-state concentration ($C_{(ss,x)}$ [kg m^{-3}]). Assuming the operation is repeated periodically, one can thus calculate the health impacts from this steady-state concentration using equation (5.i) & (5.ii). Emissions from active equipment will often contain inorganic gases (e.g., NO_x, CO, SO_2) which are respirable, and in most cases, the presence of these particles in the outdoor is not negligible. However, due to the lack of a LCIA methodology for IAQ regarding inorganic pollutants, they were not assessed in this study.

3.3 Life Cycle Impact Assessment

In the LCIA stage, a mid-point or an end-point impact assessment can be conducted. For mid-point assessment, the emissions from the LCI stage are multiplied with the characterization factors to obtain number of carcinogenic or non-carcinogenic cases per functional unit. If an end-point indicator is needed for further normalization and weighting, the mid-point

assessment value is further multiplied with a damage (severity) factor (DF) to obtain disability adjust life years (DALYs) per functional unit. For IAQ, the characterization factor can be obtained from the product of the intake fraction (iF) and the effect factor (EF). The midpoint and end-point assessment steps are shown in sections 3.i and 3.ii in Figure 3. The relevant LCIA equations can be written as following equation (adapted from Meijer et al., 2005a, 2005b).

$$\text{Damage Score}_{(x, \text{mid-point})} = \text{Emission}_{(x)} \times iF \times EF_{(x,i)}$$

Equation (2.i)

$$\text{Damage Score}_{(x, \text{end-point})} = \text{Emission}_{(x)} \times iF \times EF_{(x,i)} \times DF_{(x,i)}$$

Equation (2.ii)

Where,

$EF_{(x,i)}$ = Effect factor for chemical x for effect i (carcinogenic or non-carcinogenic) [case per kg_{intake}]

$DF_{(x,i)}$ = Damage factor for chemical x due to effect i (carcinogenic or non-carcinogenic) [DALY per case]

$\text{Emissions}_{(x)}$ = Total emission of x in the compartment over certain time period [kg]

iF = Indoor Intake Fraction ($kg_{intake}/kg_{emission}$) [-]

Equation (2.i) and (2.ii) work for any single chemical x. The total impact can be simply summed by the damage score from each chemical.

The iF can be calculated , by accounting for the fraction of time occupants stay indoor (f_{indoor}) (Humbert et al., 2011)(box 3.1 in Figure 3).

$$iF = f_{indoor} \times BR \times N \ (V \times M \times k_{ex})$$

Equation (3)

Where,

f_{indoor} = Fraction of time occupants stay indoor [-]

BR = Breathing rate [m^3 $person^{-1}$ hr^{-1}]

N = Number of occupants [persons]

V = Room volume [m^3]

M = Mixing factor [-]

k_{ex} = Air change rate (ACH) [hr^{-1}]

The EF is a measure of the change in the life time disease probability due to a change in life time intake of a pollutant (cases/kg_{intake}). The EF for inhalation and ingestion is determined separately for carcinogenic and non-carcinogenic effects (Rosenbaum et al., 2011). It is not possible to easily obtain the EF from common LCIA methods such as the Eco-Indicator 99, Impact 2002+ since these methods were developed for the outdoor environment and report the characterization factors as a lumped parameter (Dreyer et al., 2003; Humbert et al., 2012). In contrast, the USEtox model explicitly reports the EF and the iF (different inhalation and ingestion pathways for outdoor compartment) (Rosenbaum et al., 2008). For certain groups of organic compounds, the EF can be obtained directly from USEtox model to be used in Equation (2.i) and (2.ii).

$\text{Emission}_{(x)}$ is the total emission of chemical x over the compartment over the selected time period. For the long-term decayed emission from passive products (box 3.a), $\text{Emission}_{(x)}$ is changing with time and for a certain time period, is calculated as: $\text{Emission}_{(t1-t2, x)} = C_{(t1-t2, x)} \times V$.

Combining equation (2.i)/(2.ii) and equation (3), the mid-point and end-point impact scores from passive products can be calculated as:

$$DS_{(t1-t2, x, midpoint, passive product)} = C_{(t1-t2, x)} \times f_{indoor} \times BR \times N / (M \times k_{ex}) \times EF_{(x,i)}$$

Equation (4.i)

$$DS_{(t1-t2, x, endpoint, passive product)} = C_{(t1-t2, x)} \times f_{indoor} \times BR \times N / (M \times k_{ex}) \times EF_{(x,i)} \times DF_{(x,i)}$$

Equation (4.ii)

For active equipment, $Emission_{(x)}$ over one year operation is estimated from the steady-state concentration, $C_{(ss, x)}$ as: $Emission_{(x)} = C_{(ss,x)} \times Q \times R_{ep}$, where Q is the make-up air [m^3 hr^{-1}] and calculated as $V \times k_{ex}$ (assuming no infiltration/exfiltration and recirculation, make-up air equals exhaust air flow), R_{ep} is the repeating hours within each time period (i.e., operation hours per year). Combining equation (2.i)/(2.ii) and equation (3), the mid-point and end-point scores from active equipment can be calculated as:

$$DS_{(ss, x, midpoint, active equipment)} = C_{(ss,x)} \times f_{indoor} \times BR \times N / M \times R_{ep} \times EF_{(x,i)}$$

Equation (5.i)

$$DS_{(ss, x, endpoint, active equipment)} = C_{(ss,x)} \times f_{indoor} \times BR \times N / M \times R_{ep} \times EF_{(x,i)} \times DF_{(x,i)}$$

Equation (5.ii)

The last step of an LCA is the interpretation. For an IAQ related study, it is carried out similarly with other LCA studies. Since IAQ is strongly affected by the indoor air exchange, it is strongly recommended that the sensitivity analysis regarding important input parameters, such as the air exchange rate is to be modelled under different scenarios.

4. IMPLEMENTATION OF THE PROPOSED FRAMEWORK

In this section, we briefly present three hypothetical examples where the proposed framework was applied to estimate mid-point impacts from inhalation of organic compounds from building related products. The examples are not real case studies and are provided only to demonstrate the proposed framework and calculation procedure. End-point results and details of the calculations and parameters used in the examples are provided in the SI. The first example is from the passive product category where the emission rate is dynamic and declines over time. The second and third examples are from the active equipment category where the emission rate is constant during the operation of the equipment.

4.1 Example 1: Passive Product - Alkyd Primer

An alkyd primer was chosen with parameters obtained from (Guo et al., 1999). The primer was assumed to be applied over the interior walls and ceiling, without further paint applied on top of it. The estimated service time for the primer was 10 years. We used the first order exponential decay model when modelling the emission from the primer (Guo et al., 1999), assuming one-compartment model. Initially, 15 types of organic compounds were obtained from (Guo et al., 1999), but only three of them have the EFs from the USEtox model. The results showed that almost all the emissions occurred within one day (Figure S.1 in SI), and consequently, impacts occurring after the day of application became trivial (Table 1). The mid-point impacts over the time of application to the time of achieving maximum concentration and the time of maximum concentration to one day are presented in Table 1.

Table 1: Mid-point damage scores of base scenarios from the passive product application and the active equipment operation

Example 1_passive product		Carcinogenic	Non-carcinogenic
Alkyd primer	Total impacts over service time (cases)	2.19E-6	4.83E-7
	Impacts from t_0 to t_{max} (% of total)	18%	12%
	Impacts from t_{max} to one day (% of total)	82%	88%
Example 2_active equipment (combustion source)		Carcinogenic	Non-carcinogenic
Natural stove	Total impacts over one year operation (cases)	8.85E-06	4.47E-06
Example 3_active equipment (electric source)		Carcinogenic	Non-carcinogenic
Desktop total	Total impacts over one year operation (cases)	2.90E-08	3.93E-10
Notebook (use)		9.57E-13	1.10E-12
Notebook (idle)		3.55E-12	3.76E-12

Note: t_0 is the time right after application; tmax is the time to reach the maximum concentration of chemical$_x$, t_{max} is different for different chemicals. The final damage scores were aggregated from different chemicals during that time period.

4.2 Example 2: Active Equipment by Combustion Source - Natural Gas Stove

Cooking and environmental tobacco smoke are two major sources of indoor pollutants and there is evidence for a modest risk of gas cooking on health (Chauhan, 1999). While smoking can be avoided totally, cooking activity is a "must-have" in the majority of most households. Thus, it is included as an example to illustrate how to integrate it into the whole-building LCA.

The emission profile from cooking depends on the cooking appliance and fuel type, and to a lesser extent, by the meal type, the meal size, and the cooking method. In this example, the natural gas stove was modeled as the cooking method and the emission rate was assumed to be the same for each day. We assumed that the cooking was repeated in 300 days each year. The emission factors ($mg_{emission}/kg_{fuel}$) were obtained from (Tsai et al., 2003). However, since this data set was collected in the period of 1995 to 1996 from an unvented gas stove, the data was modified to include an assumed stove efficiency of 80% and a flue efficiency of 80%. Detailed assumptions and calculation procedures can be found in S.2.2 of SI. Initially, 27 types of organic compounds were obtained from (Tsai et al., 2003), only seven of them have effect factors from USEtox model. The mid-point impact results over one year period are presented in Table 1. The biggest impact was from benzene, due to its higher emission rate (50mg per kg of natural gas) than other chemicals (mostly less than 1mg per kg of natural gas).

4.3 Example 3: Active Equipment by Electric Source – Computers

A previous study found personal computers (PC) as an un-neglectable indoor pollution source (Bakó-Bíró et al., 2004). To demonstrate the framework, both a desktop computer with TFT monitor and notebook computers were modelled. The emission factor for both the desktop and notebook came from (Destaillats et al., 2008). It was assumed that a household has one desktop computer, two notebooks, and the usage was repeated 300 days a year, 1 hour each day

for each computer/notebook. The mid-point impact results over one year period are presented in Table 1. The impacts caused by computers were much lower than impacts from natural gas stove. Among the computers, impacts from desktop overweighed notebook in every aspect.

4.4 Scenarios with Doubled Air Change Rate

When the air change rate was doubled for the first example, both the maximum concentration and the time to reach it reduced for all the chemicals. The final impacts during different time intervals reduced by a little over or less than half due to the non-linearity between the air change rate and the final impacts. For examples 2 and 3, the input building parameters were linearly related with the final damage scores. In other words, by increasing the air change rate by 50%, the final damage scores were reduced by 50%. Other parameters such as occupants' numbers and fraction of time spent indoor were reversely proportional to the damage scores.

5. DISCUSSION

With the IAQ-LCA results obtained from the above hypothetic examples, it is natural to ask how the IAQ impacts on human health from a product compares to its non-IAQ health impacts from its other life cycle stages. Unfortunately, to the knowledge of the authors, either no publicly-available LCA studies exist or they do not assess human health impacts (Sto, 2011; Jungbluth, 1997; Boyd et al., 2009; Stutz, 2011). It was not possible to compare the results from the examples with data from EIO-LCA model either, since the current EIO-LCA model uses an earlier version of TRACI method which does not report health impacts in carcinogenic and noncarcinogenic cases (Carnegie Mellon University Green Design Institute, 2008; Bare, 2012). Further studies need to be carried out to compare the IAQ related impacts with non-IAQ impacts from different life cycle stages.

The results showed that the daily operation of natural gas stove posed higher impacts than the primer and computers. However, since only one kind of passive products was modeled, the results are not representative of other types of passive products. For example, compared with wet products which cause most of the impacts during initial short period (e.g., the primer we assessed here), other passive products can show more persistent emissions for extended times (Christianson et al., 1993; Yu & Crump, 1998). For the wet product modelled in example 1, the health impacts caused by initial emissions can be avoided by moving into the building after a few days of the application. Thus the painter/decorator who stays indoor after the application of primer is subject to higher life time risk from inhalation of emissions than the building occupants who live in the building for up to 10 years. As shown in the scenario analysis, increasing the air change rate could reduce the initial indoor emissions and associated health impacts.

For the framework, in the LCI stage, three ways of data obtaining methods were identified and two of them (collecting data through previous studies and through IAQ modelling) were demonstrated in the three examples. Most of the time, there is an overlap between collection and modelling of IAQ data, since the collected data (e.g., emission factors) needs to be put into the IAQ model. The IAQ-related emission factors during the operational stage of a building are not as available as the emission factors used in other life cycle stages of the product (e.g., cradle to gate emissions from the LCI databases). Furthermore, not all emission sources can be modelled and even if the emission can be obtained through IAQ modelling, the trade-offs between model simplicity and accuracy should be considered.

In the LCIA stage, the accuracy of the results relied on the accurate estimation of building parameters which caused model uncertainties. Besides, the biggest difficulty lies in the completeness and availability of the LCIA model. For all the three examples, the secondary data collected consisted of chemicals that could not be found in the USEtox model. As depicted in the framework, we did not include human health impacts from inorganic pollutants (box 3.i.1 and 3.i.3) due to the lack of LCIA model for their emissions into indoor environment; this is one of the limitations of this study.

The ultimate vision for the framework is to integrate the building related product LCA into the whole-building LCA. In doing so, it will be important to use the same LCIA method to obtain consistent results. For instance, in the IMPACT 2002+ v2.1, the default value for DALY is 13 years per case for carcinogenic effect and 1.3 years per case for non-carcinogenic effect, while in IMPACT 2002+ v2.0, the values for the same parameters are 6.7 and 0.67 respectively (Humbert et al., 2012).

6. CONCLUSIONS

This study proposed a thorough framework for integrating IAQ into building and building related products LCA studies. A modular approach was suggested where first the independent LCA of building related products could be carried out; then this product LCA could be further integrated into the whole-building LCA. Depending on different emission profiles, two categories of building related products were illustrated under the framework: passive products and active equipment.

The time period for the functional unit of passive products and active equipment were proposed differently. The build-up of LCI took different approaches depending on the emission profiles of the assessed subject. For passive products, a dynamic LCI was constructed, while for the active equipment static LCI were obtained. Current LCIA methodology and the characterization factors can be applied to the inventory result, with a modified indoor intake fraction. Nevertheless, due to the lack of LCIA methodology, inorganic pollutants were not assessed and only part of the organic compounds that built up in the LCI stages were assessed.

Through the proposed framework and examples, it was demonstrated that integrating IAQ into building related LCA studies was practical. To compare the relative contributions on human health impacts from IAQ sources with other activities and life cycle stages, further studies need to be carried out. Nevertheless, since the early design stage, the building usage pattern and key building parameters could be either determined (e.g., volume, occupancy number) or subject to change (e.g., ventilation systems). Thus, instead of keeping IAQ aside and address it later in the occupancy stage, it should be considered and integrated into the early design stage of the building construction or renovation.

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SUPPLEMENTARY INFORMATION FOR FRAMEWORK FOR INTEGRATING INDOOR AIR QUALITY IMPACTS INTO LIFE CYCLE ASSESSMENTS OF BUILDINGS AND BUILDING RELATED PRODUCTS

S.1. IAQ MODELLING

S.1.1. IAQ modelling for passive products with dynamic emission rate

For emissions from passive products (most of the time VOCs), they are decayed emission over a long time period. For different kinds of products, different decaying models may be applied according to Brown (Brown, 2009):

- First order exponential decay: decreasing from high initial levels to near-zero levels (e.g., some wet paint and coatings).
- Double-exponential decay: decreasing from high initial levels to near-constant (or slow decay) levels (e.g., some carpets and floor coverings) [cross ref. brown 1999b, chamber assessment of formaldehyde and VOC emissions]
- Delayed first-order decay: increasing from near-zero levels to pass through a peak emission several hours after application/manufacture (e.g., aldehyde formation by auto-oxidation of fatty acids in alkyd paints, vegetable oil products) [cross ref. Chang, 1999 evaluation of low-VOC latex paints]

Most of the time, different models exist for predicting the same type of material. For example, for wet materials like paint, (Won et al., 2003) proposed using three different models in sequence depending on elapsed time (a vapor pressure and boundary layer model, an exponential decay model and a power-law decay model). Trade-offs between simplicity versus accuracy should be considered when choosing the model, which should reflect the ultimate goal of the study.

No matter which model is used, the basic theory is the mass balance. For one-compartment, a mass balance model can be written as equation S.1 (same as equation 1 in the manuscript) (Kumar & Vempati, 2013):

$$V (dC_{(t,x)}dt) = M \times Q_0 \times C_o \times (1-F_0) + M \times Q_1 \times C_{(t,x)} \times (1-F_1) + M \times Q_2 \times C_o + S - M \times Q_3 \times C_{(t,x)} - M \times Q_4 \times C_{(t,x)} - R$$

Equation S.1

Where,

$C_{(t,x)}$ = Instantaneous indoor concentration of chemical x at time t [mg m^{-3}]
Q_0 = Make-up air [m^3 hr^{-1}]
Q_1 = Indoor air recirculation [m^3 hr^{-1}]
Q_2 = Infiltration from outdoors [m^3 hr^{-1}]
Q_3 = Exfiltration from indoors [m^3 hr^{-1}]
Q_4 = Exhaust flow rate [m^3 hr^{-1}]
F_0 = Filter efficiency (for the outside air) [-]
F_1 = Filter efficiency (for the recirculated air) [-]
C_0 = Outside concentration [mg m^{-3}]
V = Room volume [m^3]

M = Mixing factor [-]
S = Source Emission Rate [mg hr^{-1}]
R = Decay of Pollutant [mg hr^{-1}]

For the first order decayed material, using one-compartment modelling, the emission rate can be calculated based on equation S.1. In the following equations, to clarify symbols involving "k": k_{ex} is the air change rate, $K_{(x)}$ which is the decay rate constant for chemical x and k(m,x) and is the gas-phase mass transfer coefficient for chemical x.

Since the outdoor concentration of chemicals that are typically found in building materials (organic compounds) is rather low, such chemicals entering indoor is negligible (C_0 = 0), assuming mixing factor being 1; no infiltration / exfiltration, no recirculated air ($Q_1=Q_2=Q_3=0$); no sink / removal indoor, the above equation becomes:

$$V(dC(t,x)dt) = S - Q_4 C_{t,x} = A E_{t,x} - Q_4 C(t,x)$$

Equation S.2

Where,

A = the source area [m^2]

$E_{(t,x)}$ = emission factor for chemical x emitted by emission source x at time t [mg m^{-2} h^{-1}]
For first order decay, from Guo et al. (Guo, Chang, Sparks, & Fortmann, 1999), $E_{(t,x)}$ can be calculated by:

$$E(t,x) = E(0,x)\exp(-K(x)t)$$

Equation S.3

Where,

$E_{(0,x)}$ = initial emission rate for chemical x [mg m^{-2} hr^{-1}]

$K_{(x)}$ = first-order decay rate constant for chemical x [hr^{-1}]

t = time [hr]

$E_{(0,x)}$ and K(x) from equation S.3 can be calculated using two mass transfer models proposed by (Guo et al., 1999):

$$E(0,x) = k(m,x) \; C(v,x) \; mmx \; yxy0 = k(m,x) \; px\textit{760} \; mvm \; yxy0$$

Equation S.4

Where,

m = average molecular weight for TVOC [g mole^{-1}]

m_x = molecular weight for component x [g mole^{-1}]

y_0 = TVOC content in the product, [mg g^{-1}]

y_x = content of component x in the product [mg g^{-1}]

$k_{(m,x)}$ = gas-phase mass transfer coefficient for chemical x [m h^{-1}]

$C_{(v,x)}$ = concentration of component x at air/source interface, based on the vapor pressure of component x [mg m^{-3}]

P_x = vapor pressure the chemical x [mmHg]

v_m = volume of 1 mole gas under 1 atm [m^3] (0.0243 m^3 at 23°C).

760 = the unit conversion factor [mmHg atm^{-1}]

Average molecular weight for TVOC (m) is calculated as:

$$m = \frac{\sum_{x=1}^{n} y_x}{\sum_{x=1}^{n} (y_x / m_x)}$$

Equation S.5

Individual decay rate constant for chemical x is calculated as:
$$K_{(x)} = E_{(o,x)}(\theta \, d \, y_x)$$

<div align="right">Equation S.6</div>

Where,

θ = wet film thickness, [m]

d = product density, [g m^{-3}]

Plug equation S.3 to equation S.2 and solve the differential equation, the instantaneous concentration of chemical x indoor (mg m^{-3}):

$$C_{(t,x)} = \frac{A \, E_{(0,x)}}{V \, (k_{ex} - K_{(x)})} \left[\exp(-K_{(x)}t) - \exp(-k_{ex}t)\right]$$

<div align="right">Equation S.7</div>

By integrating $C_{(t,x)}$ over certain time interval, the cumulative concentration over that time can be obtained. Therefore, it will be possible to see the health impacts from different periods by such dynamic inventory (mg m^{-3} over time interval t1 to t2)

$$C_{(t1-t2,x)} = \int_{t1}^{t2} C_{(t,x)} \, dt$$

<div align="right">Equation S.8</div>

S.1.2. IAQ modelling for active equipment with constant emission rate

For calculation of emissions from operational use of equipment, it was assumed the emission occurs at a constant rate during the operation and repeated periodically throughout the year, the same mass balance model (equation S.1) is used.

Assuming mixing factor to be 1, no pollutant decay (except for O_3), no infiltration and exfiltration, no recirculated air, and for organic compounds with negligible outdoor concentration (C_0), the equation is reduced to:

$$C_{(ss,x)} = SQ0 = S(V \, k_{ex})$$

<div align="right">Equation S.9</div>

Where,

S = the Source Emission Rate, with constant emission rate, [mg hr^{-1}]

S.2. Calculation, data tables and results for the three examples

The input parameters for the IAQ modelling was summarized in Table S.1, they were used for all three examples.

We summarized important calculations and results for each example through S.2.1 to S.2.3.

S.2.1. Example 1

The alkyd primer characteristics and parameters are obtained from (Guo et al., 1999) as follows: Product density (d) is 1.33E+06 g m^{-3}; Wet film thickness (θ) is 8.25E-05 m; Average molecular weight for TVOC (m) is 1.32E+02 g mole^{-1}; Mass transfer coefficient$_{(kmx)}$ is 4.36E+00 m hr^{-1}; and TVOC content (y_0) is 7.86E+01 mg g^{-1}. In Table S.2, alkyd primer parameters are calculated from above characteristics.

Table S.1: Building parameters used in the IAQ modelling for calculation LCI data

Parameters	Value	Unit	Comments
Fraction of time spent indoor (f_{indoor})	0.5		Assumes occupants spend around 12 hours each day in the house
Room dimension (V)	10 * 10 * 2	m^3	Assumed
Source area (A)	180	m^2	Assumed
Make up air (Q_o)	100	$m^3\,hr^{-1}$	Calculated by $k_{ex} * V$
Number of occupants (N)	3	persons	Assumed
Breathing Rate (BR)	0.625	m^3 per hr per person	Default value from US EPA (USEPA, 2011)
Air changes per hour, ACH (k_{ex})	0.5	hr^{-1}	Assumed
Mixing factor (M)	1		Assumed

Table S.2: Alkyd primer's parameters for individual ingredient

| Chemical (x)	y_x (mg/g)	m_x (g/mole)	p_x (mmHg)	y_x/m_x	$E_{(0,x)}$ [mg/m^{2}hr] Equation S.4	$k_{(x)}$ [hr^{-1}] Equation S.6
	known parameters			calculated parameters		
Decane	3.07E+01	1.42E+02	1.58E+00	2.16E-01	1.92E+04	5.70E+00
Nonane	1.84E+01	1.28E+02	4.14E+00	1.44E-01	3.03E+04	1.50E+01
Octane	1.56E+01	1.14E+02	7.89E+00	1.37E-01	4.89E+04	2.86E+01
Undecane	6.68E+00	1.56E+02	6.16E-01	4.28E-02	1.63E+03	2.23E+00
trans-Decalin	2.28E+00	1.38E+02	3.30E+00	1.65E-02	2.98E+03	1.19E+01
2-Methyldecane	2.19E+00	1.70E+02	6.16E-01	1.29E-02	5.36E+02	2.23E+00
p-Xylene	1.39E+00	1.06E+02	7.71E+00	1.31E-02	4.26E+03	2.79E+01
Toluene	3.50E-01	9.20E+01	2.45E+01	3.80E-03	3.40E+03	8.85E+01
Ethylbenzene	2.90E-01	1.06E+02	8.85E+00	2.74E-03	1.02E+03	3.20E+01
o-Xylene	2.30E-01	1.06E+02	5.90E+00	2.17E-03	5.39E+02	2.13E+01
p-Ethyltoluene	2.10E-01	1.20E+02	2.86E+00	1.75E-03	2.39E+02	1.04E+01
1,2,4-Trimethylbenzene	1.40E-01	1.20E+02	2.03E+00	1.17E-03	1.13E+02	7.34E+00
Dodecane	6.30E-02	1.70E+02	2.53E-01	3.71E-04	6.33E+00	9.15E-01
n-Propylbenzene	3.40E-02	1.20E+02	3.13E+00	2.83E-04	4.22E+01	1.13E+01
1,3,5-Trimethylbenzene	2.30E-02	1.20E+02	2.53E+00	1.92E-04	2.31E+01	9.14E+00

Instantaneous concentration $C_{(t)}$ is calculated according to equation S.7 and presented in Figure S.1. In table S.3, only three chemicals are presented since in the later LCIA stage, effect factors are only available for these three chemicals.

Mid-point Effect Factors [cases mg$_{inhaled}^{-1}$] obtained from USEtox model for cancer and non-cancer effects of Toluene are: 0 and 3.64E-09; of Ethylbenzene are: 2.36E-08 and 3.85E-10; and of 1,2,4-Trimethylbenzene are: 2.64E-10 and 0. Final damage scores are calculated according to equation 4.i and 4.ii in the manuscript and presented in Table S.3.

Table S.3: Concentrations $C_{(t1-t2)}$ [mg m^{-3}] and damage scores (midpoint [cases] & endpoint [DALY]) at different time intervals from alkyd primer

	Chemical	0 to max t = 0 - tmax		max to one day t = tmax - 24		one day to one week t = 24 - 168		one week to one month t = 168 - 720		one month to half year t = 720 - 4380	
Concentrations (C(t1-)	Toluene	7.26E+00		5.84E+01		4.28E-04		2.30E-35		2.30E-155	
	Ethylbenzene	8.84E+00		4.03E+01		3.58E-04		1.92E-35		1.93E-155	
	1,2,4-Trimethylbenzene	3.37E+00		2.42E+01		1.82E-04		9.79E-36		9.79E-156	
Damage Score (midpoint)	Toluene	0.00E+00	4.95E-08	0.00E+00	3.98E-07	0.00E+00	2.92E-12	0.00E+00	1.57E-43	0.00E+00	1.57E-163
	Ethylbenzene	3.91E-07	6.39E-09	1.78E-06	2.91E-08	1.58E-11	2.58E-13	8.51E-43	1.39E-44	8.51E-163	1.39E-164
	1,2,4-Trimethylbenzene	1.67E-09	0.00E+00	1.20E-08	0.00E+00	8.99E-14	0.00E+00	4.83E-45	0.00E+00	4.84E-165	0.00E+00
	Total DS (midpoint)	3.93E-07	5.59E-08	1.79E-06	4.27E-07	1.59E-11	3.17E-12	8.56E-43	1.71E-43	8.56E-163	1.71E-163
Damage Score (endpoint)	Toluene	0.00E+00	6.43E-08	0.00E+00	5.18E-07	0.00E+00	3.79E-12	0.00E+00	2.04E-43	0.00E+00	2.04E-163
	Ethylbenzene	5.08E-06	8.31E-09	2.31E-05	3.78E-08	2.06E-11	3.36E-13	1.11E-41	1.81E-44	1.11E-161	1.81E-164
	1,2,4-Trimethylbenzene	2.17E-08	0.00E+00	1.55E-07	0.00E+00	1.17E-12	0.00E+00	6.29E-44	0.00E+00	6.29E-164	0.00E+00
	Total DS (endpoint)	5.11E-06	7.26E-08	2.33E-05	5.56E-07	2.07E-10	4.13E-12	1.11E-41	2.22E-43	1.11E-161	2.22E-163

Figure S.1: Instantaneous concentration C(t) for selected chemicals from alkyd primer
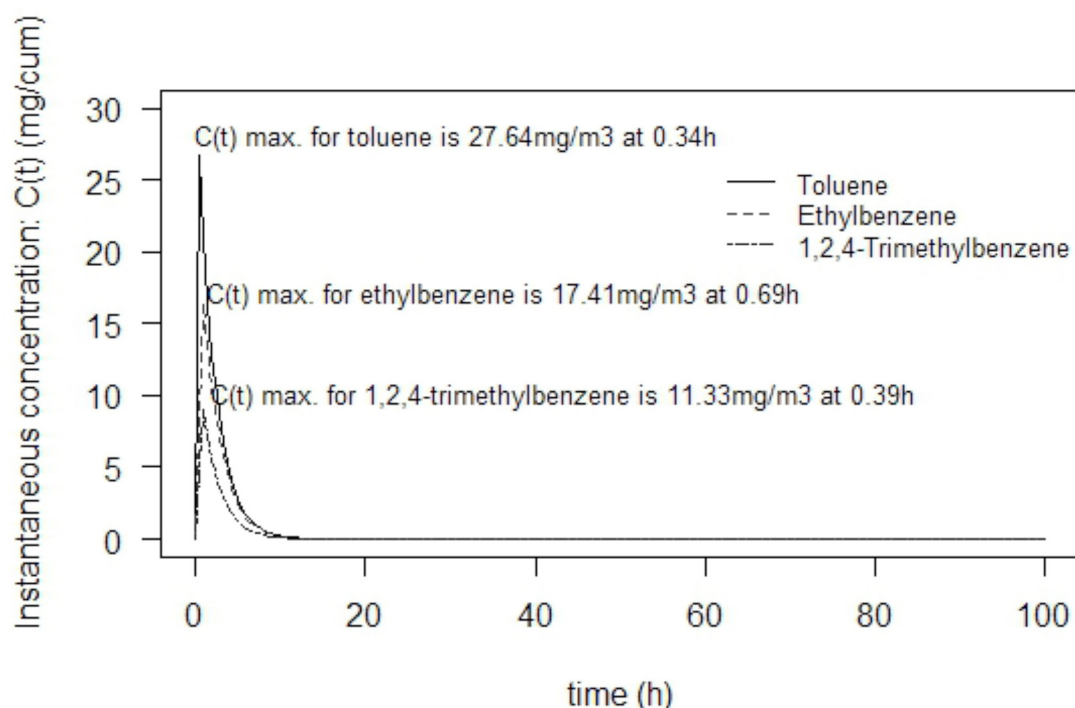
R code to calculate the maximum concentration and draw the concentration curve:

```
#Toluene concentration formular C(t,x) = -34.8 * ( e ^(-8.85 t) - e ^(-0.5 t) )
Ctl <- function(t) -34.8  * ( exp(-t * 8.85) - exp(-t * 0.5) )
curve(Ctl, 0, 50, las=1, lwd=1.5, xlab = "time (h)", ylab = "Instantaneous concentration:
    C(t) (mg/cum)", lty = 1, col="black", xlim = c(0,100), ylim = c(0,30))
optimize(Ctl, interval=c(0, 400), maximum=TRUE)
#Ethylbenzene concentration formular  C(t,x) = -29.1 * ( e ^(-3.2 t) - e ^(-0.5 t) )
Ceb <- function(t) -29.1 * ( exp(-t * 3.2) - exp(-t * 0.5) )
curve(Ceb, 0, 100, add = T, xlab = "time (h)", ylab = " C(t) of ethylbenzene (mg/cum)",
    lty = 2, col="gray20")
optimize(Ceb, interval=c(0, 100), maximum=TRUE)
#1,2,4-Trimethylbenzene concentration formular  C(t,x) = -14.8 * ( e ^(-7.34 t) - e ^
    (-0.5 t) )
Ctb <- function(t) -14.8  * ( exp(-t * 7.34) - exp(-t * 0.5) )
curve(Ctb, 0,100,  add = T, lwd=1.5, xlab = "time (h)", ylab = "C(t) of 1,2,4-trimethyl
    benzene (mg/cum)", lty = 6, col="gray10")
optimize(Ctb, interval=c(0, 100), maximum=TRUE)
legend(60,27, bty="n", c("Toluene","Ethylbenzene","1,2,4-Trimethylbenzene"), col=
    c("black","gray20","gray10"), lty = c(1,2,6), cex=0.8)
```

text(0.1,28, "C(t) max. for toluene is 27.64mg/m3 at 0.34h", cex=0.8, adj = 0)

text(1.5,17, "C(t) max. for ethylbenzene is 17.41mg/m3 at 0.69h", cex=0.8, adj = 0)

text(2,10, "C(t) max. for 1,2,4-trimethylbenzene is 11.33mg/m3 at 0.39h", cex=0.8, adj = 0)

#intergrate for Toluene over different time invervals:

Ttl = matrix(data = c(0, 0.344133, 0.344133,24, 24,168, 168,720, 720,4380, 4380,8760, 8760,87600), ncol = 2, byrow=T)

INTtl=c()

for (i in 1:7) {INTtl[i] = integrate(Ctl, lower=Ttl[i,1], upper=Ttl[i,2]) }

#intergrate for Ethylbenzene over different time invervals:

Teb = matrix(data = c(0, 0.6875, 0.6875,24, 24,168, 168,720, 720,4380, 4380,8760, 8760,87600), ncol = 2, byrow=T)

INTeb=c()

for (i in 1:7) {INTeb[i] = integrate(Ceb, lower=Teb[i,1], upper=Teb[i,2]) }

#intergrate for 1,2,4-Trimethylbenzene over different time invervals:

Ttb = matrix(data = c(0, 0.3927809, 0.3927809,24, 24,168, 168,720, 720,4380, 4380,8760, 8760,87600), ncol = 2, byrow=T)

INTtb=c()

for (i in 1:7) {INTtb[i] = integrate(Ctb, lower=Ttb[i,1], upper=Ttb[i,2]) }

S.2.2. Example 2

To calculate the emission from natural gas cooking stove, first, the heat (Q) needed for cooking the food is calculated:

$$Q = c×meal×\Delta T$$

<div align="right">Equation S.10</div>

Where,

Q = Heat needed for cooking [KJ]

c = specific heat for food [KJ kg^{-1} ^{o}C^{-1}]

meal = average consumption of food per household per day [kg]

ΔT = the temp difference during cooking [^{o}C]

TABLE S.4: Selected food consumption for the household

Food Type	Specific heat (KJ kg^{-1} ^{o}C^{-1}) Source: EngineeringToolbox (2014)	Assumed average consumption per day per household (kg)	ΔT (Assume room temp. 20 ^{o}C meat/fish is cooked to 100 ^{o}C and vegetables to 80 ^{o}C)	Heat needed for cooking (KJ) Equation S.10
Beef, round	3.1	0.2	80	49.6
Chicken, hens	2.72	0.2	80	43.52
Figs, fresh	3.43	0.3	80	82.32
Lettuce	4.02	0.6	60	144.72
Onions	3.77	0.2	60	45.24
Tomatoes, red	3.98	0.4	60	95.52
Water	4.19	1	80	334.88

Two more equations were applied when calculating final emission rate indoors:

$$\text{fuel}_{cons} = Q_{all}(\text{fuel}_{ec} \times \eta_{stove})$$

<div align="right">Equation S.11</div>

Where,

fuel_{cons} = Fuel consumption per day [kg_{fuel} day^{-1}]

Q_{all} = Total heat required for preparing the food for a typical household each day [MJ day^{-1}]

Fuel_{ec} = Fuel energy content [MJ kg^{-1}]

η_{stove} = stove efficiency [%]

$$\text{Emission}_{(x)} = \text{EmF}_{(x)} \times \text{fuel}_{cons} \times (1 - \eta_{flue})$$

<div align="right">Equation S.12</div>

Where,

$\text{Emission}_{(x)}$ = Emission rate indoor for chemical x [mg day^{-1}]

$\text{EmF}_{(x)}$ = Emission factor of chemical x (mg kg_{fuel}^{-1})

η_{flue} = flue efficiency [%]

The cooking parameters used for calculating emission rate from natural gas stove are: the fuel energy content for natural gas is 51.3 MJ kg^{-1}, this is obtained from (Tsai et al., 2003); stove efficiency and flue efficiency are both assumed as 80%; heat required for cooking is 795.8 KJ day^{-1}, calculated from Table S.4; fuel consumption per day is 0.02 kg, calculated from Equation S.11.

TABLE S.5: Calculated constant emission rate and concentrations C(ss,x) from natural gas stove

Chemicals	Emission Factor [mg kg^{-1}] from Tsai et al. (Tsai et al., 2003)	Emission Rate [mg day^{-1}] Equation S.12	Concentrations [mg m^{-3}] Equation S.9
benzene	5.00E+01	1.94E-01	8.08E-05
xylenes (o+m+p)	1.76E+01	6.83E-02	2.84E-05
styrene	6.91E-01	2.68E-03	1.12E-06
ethane	7.92E+00	3.07E-02	1.28E-05
ethylene	5.72E+00	2.22E-02	9.24E-06
acetylene	1.19E+00	4.62E-03	1.92E-06
propane	4.28E+00	1.66E-02	6.92E-06
propene	9.91E-01	3.84E-03	1.60E-06
i-butane	1.31E+00	5.08E-03	2.12E-06
i-butene	1.38E-01	5.35E-04	2.23E-07
1-butene	6.90E-02	2.68E-04	1.11E-07
n-butane	1.58E+00	6.13E-03	2.55E-06
trans-2-butene	9.50E-01	3.68E-03	1.54E-06
cis-2-butene	5.60E+00	2.17E-02	9.05E-06
i-pentane	4.03E-01	1.56E-03	6.51E-07
1-pentene	1.21E+00	4.69E-03	1.96E-06
n-pentane	5.53E-01	2.14E-03	8.94E-07
2-methylpentane	3.46E-01	1.34E-03	5.59E-07
n-hexane	3.11E-01	1.21E-03	5.03E-07
methylcyclopentane	4.60E-02	1.78E-04	7.43E-08
2-methylhexane	5.20E-02	2.02E-04	8.40E-08
2,3-dimethylpentane	1.90E-01	7.37E-04	3.07E-07
3-methylhexane	6.10E-01	2.37E-03	9.86E-07
n-heptane	1.96E-01	7.60E-04	3.17E-07
toluene	1.73E+01	6.71E-02	2.80E-05
n-octane	2.30E-01	8.92E-04	3.72E-07
ethylbenzene	1.57E+00	6.09E-03	2.54E-06

TABLE S.6: Midpoint effect factors and damage scores (mid-point and end-point) from natural gas stove

Chemical	Effect factor [cases/mg$_{intake}$]		DS (midpoint) [cases]		DS (endpoint) [DALY]	
	cancer	non cancer	cancer	non cancer	cancer	non cancer
benzene	1.47E-08	3.72E-09	8.00E-06	2.03E-06	1.04E-04	2.63E-06
xylenes (o+m+p)	3.69E-10	8.58E-09	7.08E-08	1.65E-06	9.20E-07	2.14E-06
styrene	4.92E-08	9.84E-09	3.71E-07	7.42E-08	4.82E-06	9.64E-08
i-butene	3.23E-10	0.00E+00	4.86E-10	0.00E+00	6.32E-09	0.00E+00
n-hexane	6.74E-11	9.16E-09	2.28E-10	3.11E-08	2.97E-09	4.04E-08
toluene	0.00E+00	3.64E-09	0.00E+00	6.86E-07	0.00E+00	8.92E-07
ethylbenzene	2.36E-08	3.85E-10	4.04E-07	6.60E-09	5.25E-06	8.58E-09
		Total DS	8.85E-06	4.47E-06	1.15E-04	5.81E-06

S.2.3. Example 3

TABLE S.7: Emission Rate [ug hr-1] and steady-state concentrations Css [ug m-3] for computers

Chemicals	Emission Rate [ug hr^{-1}] per unit (Source: Destaillats et al., 2008)			Total per hour assuming 1 piece of desktop and 2 pieces of notebooks			Steady-state concentrations C$_{ss}$ [ug m^{-3}]		
	Desktop (TFT monitor)	Notebook	Notebook(idle)	Desktop (TFT monitor)	Notebook	Notebook(idle)	Desktop (TFT monitor)	Notebook	Notebook(idle)
Toluene		0.04	0.15		0.08	0.3	0	0.0008	0.003
C6-C10 aromatics	32			32			0.32	0	0
Formaldehyde	9.7			9.7			0.097	0	0
Acetaldehyde	1.5			1.5			0.015	0	0
Valeraldehdye	0.5			0.5			0.005	0	0
Hexaldehyde	2.7			2.7			0.027	0	0
Methylcarbonate		0.73	1.3		1.46	2.6	0	0.0146	0.026
Ethylcarbonate		0.37	0.78		0.74	1.56	0	0.0074	0.0156
Cyclohexanone		0.07	0.21		0.14	0.42	0	0.0014	0.0042
2-Butoxyethanol		0.82	2.14		1.64	4.28	0	0.0164	0.0428
2-Ethyl-1-hexanol		0.14	0.52		0.28	1.04	0	0.0028	0.0104
Acetophenone		0.05	0.11		0.1	0.22	0	0.001	0.0022
Trimethyl		0.13	0.34		0.26	0.68	0	0.0026	0.0068
Cyclohexyl		0.16	0.81		0.32	1.62	0	0.0032	0.0162
∑VOC	113			113			1.13	0	0

TABLE S.8: Mid-point effect factor and damage score (mid-point and end-point) from computers

chemical	Effect Factor (cases/ug intake)		DS (midpoint)					
			Desktop (TFT monitor) (cases)		Notebook (cases)		Notebook(idle) (cases)	
	cancer	non cancer	cancer	non cancer	cancer	non cancer	cancer	non cancer
Toluene	0.00E+00	3.64E-09	0.00E+00	0.00E+00	0.00E+00	8.18E-10	0.00E+00	3.07E-09
Formaldehyde	1.06E-06	8.47E-09	2.90E-05	2.31E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Acetaldehyde	7.49E-09	3.85E-08	3.16E-08	1.62E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Cyclohexanone	0.00E+00	2.75E-10	0.00E+00	0.00E+00	0.00E+00	1.08E-10	0.00E+00	3.25E-10
2-Ethyl-1-hexanol	1.21E-09	0.00E+00	0.00E+00	0.00E+00	9.57E-10	0.00E+00	3.55E-09	0.00E+00
Acetophenone	0.00E+00	6.01E-10	0.00E+00	0.00E+00	0.00E+00	1.69E-10	0.00E+00	3.72E-10
Total DS (cases)			2.90E-05	3.93E-07	9.57E-10	1.10E-09	3.55E-09	3.76E-09
			DS (endpoint)					
			Desktop (TFT monitor) (DALY)		Notebook (DALY)		Notebook(idle) (DALY)	
			cancer	non cancer	cancer	non cancer	cancer	non cancer
Toluene			0.00E+00	0.00E+00	0.00E+00	1.06E-09	0.00E+00	3.99E-09
Formaldehyde			3.76E-04	3.00E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Acetaldehyde			4.11E-07	2.11E-07	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Cyclohexanone			0.00E+00	0.00E+00	0.00E+00	1.41E-10	0.00E+00	4.22E-10
2-Ethyl-1-hexanol			0.00E+00	0.00E+00	1.24E-08	0.00E+00	4.62E-08	0.00E+00
Acetophenone			0.00E+00	0.00E+00	0.00E+00	2.20E-10	0.00E+00	4.83E-10
Total DS (DALY)			3.77E-04	5.11E-07	1.24E-08	1.42E-09	4.62E-08	4.89E-09

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