Time-resolved Dynamic Disability Adjusted Life-Years Estimation

Short title: Dynamic DALYs

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Keywords

Disability Adjusted Life-Years; DALYs ;Health; IAQ assessment; Smart ventilation;

Abstract

The quantification of how healthy the indoor air is, is a complex issue comprising of a large number of contaminants of various sources. The health implication of exposure to each of the contaminant deemed of importance can be expressed using Disability Adjusted Life Years (DALYs). The sum of all DALYs indicates how harmful the indoor air was during the investigated time-frame. This metric was originally developed by the World Bank and the WHO[1]. In 2012, Logue et. al described two methods to estimate the DALYs related to exposure to contaminants in the indoor air based on the yearly mean exposure concentration of a population[2].

The downside of these methods is that, when detailed exposure concentration profiles are available, the method results in a loss of information. A novel method was developed to estimate DALYs originating from exposure to indoor pollutants that can be used for time-resolved exposure concentration data without this loss of information: Dynamic DALYs. The advantage of this method is that is can be calculated in real-time and for short or long periods of data. As such it can be used for pin-pointing problematic events in the exposure profile of a person and, as it can be calculated in real-time, makes it a candidate for use in automated optimization problems.

The use of Dynamic DALYs is demonstrated for a simulation case-study of an occupied apartment. One continuously ventilated system (Dcont) and one smart ventilation system (Dsmart) are compared. Sources of typically indoor generated Volatile Organic Compounds (VOCs) were added and the related exposure profile and Dynamic DALY results of the working adult were analyzed. The results showcase detailed and more summative results with regards to health and energy use using the novel indicator. For Dcont and Dsmart the total Dynamic DALYs are 2.2yr and 8.6yr respectively (population of 100 000, duration of 1 year) for the VOCs and sources considered in the analysis.

Practical implications

This paper describes the development of a novel method to calculate DALYs from indoor air exposure: dynamic DALYS. The dynamic DALYs method allows to quantify the harmfulness of the indoor air in real-time as well as analyze time-resolved, detailed data.

It can be used to quantify the impact of certain short-term interventions to increase indoor air quality like for example the use of a range hood while cooking or the instantaneous improvement by the use of an air-cleaner but still with the long-term health effects as the basis of the analysis. As it can evaluate the indoor air quality continuously, it can be used to optimize ventilation system controls (e.g. model predictive control or gradient decent optimization). In addition to the novel short-term analysis , it can still be used to summarize the total health impact for longer periods of time.

Introduction

Indoor Air Quality (IAQ) is a complex issue. In a typical indoor environment, a large number of contaminants is present in the indoor air of varying nature and sources. Contaminants can be chemical (e.g., volatile organic compounds), biological (e.g., airborne viruses) or physical (e.g., airborne particles). The way people interact or react to the presence of some of these contaminants is another complex issue. This interaction between people and the indoor air can be classified in two categories: the way people perceive the indoor air and the physiological effects that cause harm, simply put: comfort and health.

Historically, the focus of research concerning IAQ had a strong focus on comfort. This is due to easy-to-use correlations between peoples perceived indoor air, the bio-effluents emitted by people, and the CO2 emitted by those people breathing as well as clear comfort bands for the Relative Humidity (RH) [3]. It made, and still makes, it possible to quantify if a space is likely to be perceived by the occupants as comfortable or not without the need of surveys. As affordable sensors became available for CO_2 and RH, It also allowed the continuous monitoring of the perceived comfort and the development of smart ventilation systems[4].

For the health aspect of IAQ, quantifying if a space contains healthy air, or not, and how harmful this situation is, is less straightforward as it encompasses a wide range of potential pollutants to investigate.

For most contaminants, the exact physiological reaction is not known and not even all people react to the same contaminant in the same way. On a population level, however, a dose-response relationship can be observed between the dose of a contaminant due to exposure to a certain contaminant level and the expected rise in occurrence of a specific health outcome, the incidence. Only knowing the incidence is not enough information to be able to know how harmful the exposure to a certain contaminant is on population scale, to know this, the different health outcomes need to be weight against the severity of the symptoms. This final quantification of harmfulness can be expressed using the Disability-Adjusted Life years (DALYs) metric[5].

A DALY is the sum of the amount of life years lost in a population due to an illness or accident and the time lived with a disability (= not at full health) times the severity factor that takes into account the severity of this disability.

Following a long tradition of indicators to quantify the effectiveness of treatments and health status[6–10], the DALY metric was first introduced in 1993 in a joined effort of the world bank and the World Health Organization to quantify the cost-effectiveness of treatments[1,11]. Later in 1996 the same method was used in the first comprehensive global burden of disease study[12]. Since then, several studies and research fields worked on quantifying and predicting the harm due to certain illnesses and the relation between probable causes (e.g., exposure to a certain pollutant). The studies that found causes related to exposure to contaminants in the indoor air were aggregated by the US EPA in 1999[13]. This study provided the basis for the paper by Logue et al. in 2012, who described two methods to calculate DALYs given a population wide exposure to a certain indoor air contaminant[2].

The first method is the Intake-DALY (ID) method and is based on toxicological data (eq. 1).

$$DALYs = \left(Intake.ADAF.\frac{\partial DA\quad Cancer}{\partial intake}\right) + \left(Intake.\frac{\partial DALY_{nonCancer}}{\partial Intake}\right) \quad (1a)$$

$$Intake = V_{tot}.C_{exp,mean} \quad (1b)$$

where $\frac{\partial DA\quad i}{\partial intake}$ *[DALY/kg]* are the cancer and noncancer mass intake-based DALY factors, $Intake$ *[kg]* is the total contaminant mass intake, $C_{exp,mea,n}$ *[kg/m³]* is the mean contaminant exposure concentration, V_{tot} *[m³]* is volume of air breathed in residences each year by the whole population under investigation, and $ADAF$ [–] is the age-dependent adjustment factor.

The second method, the Intake-Incidence-DALY (IND) method is based on epidemiological data and makes use of concentration – response (C-R) functions found in literature to estimate the disease incidence (INC) as an intermediate step to calculate the DALYs (eq. 2).

$$DALYs = \left(\frac{\partial DALY}{\partial INC}\right).INC \quad (2a)$$

$$INC = -y_{0,\mathrm{yr}}.\left[e^{-\beta.\Delta C_{exp}} - 1\right].pop \quad (2b)$$

Where $\frac{\partial DALY}{\partial INC}$ is the incidence based DALY factor, $y_{0,\mathrm{yr}}$ is the baseline prevalence of the health outcome per year, β is the coefficient of the concentration change, ΔC_{exp} is the mean exposure concentration, and pop is the population size. For the population size, typically a value of 100 000 is used to calculate the expected DALYs lost in a group of 100 000 people (DALYs.100 000).

The IND method is put forward by Logue et al. as the preferred method as it doesn't require interspecies interpolation but instead is based on statistical correlations found between air quality and (increased) prevalence of a certain health outcome.

This data-driven approach has the advantage to be based on human epidemiological data but has the distinct downside that often the necessary data is unavailable or scares which makes for large uncertainties in the inputs and consequently the calculated DALYs. Additionally, regional and cultural differences (e.g. other health-care systems) or evolutions in time have the potential to shift the correlation between prevalence and air quality.

The input values for the IND method require regular updates and reviewing as more or more recent data becomes available. The prediction of DALYs for both the ID and IND method hold important uncertainties which should be considered when interpreting the results.

Development of the new metric

Dynamic DALYs

The practical downside of the Logue et al. ID and IND methods is that they require the use of the mean exposure concentration. This makes these methods less suitable when time-resolved data is available like e.g., the output of a simulation software or a measurement campaign with detailed measurement output.

In datasets with time-resolved data, it would require you to take the high-resolution data of e.g., a yearly simulation and average the occupant exposure concentration over the period of a year. Doing so, the information about when and where the harm was done to the occupant under investigation is lost.

In this research we propose a reformulation of the equations developed by Logue et al. that allows for the DALYs to be calculated in a time-resolved matter.

For the ID method, the reformulation is straightforward, namely changing the $Intake$ to the $Intake\ Rate$, $IR(t)$ as a function of time (eq. 3c). This results in a function of the gain in DALYs per unit of time $\frac{DALYs}{time}(t)$ (eq. 3b). The integral of this function over a period of time leads to a cumulative function of DALYs (eq. 3a):

$$DALYs(t) = \int_{t_0}^{t} \frac{DALYs}{time}(t) \qquad (3a)$$

$$\frac{DALYs}{time}(t) = \left(pop.IR(t).ADAF.\frac{\partial DALY_{Cancer}}{\partial intake}\right) \qquad (3b)$$
$$+ \left(pop.IR(t).\frac{\partial D \quad _{nonCancer}}{\partial Intake}\right)$$

$$IR(t) = V_{br}(t).C_{exp}(t) \qquad (3c)$$

Where $V_{br}(t)$ is the breathing rate over time. This parameter can be varied based on the occupant's metabolism. $C_{exp}(t)$ is exposure concentration profile. , pop is the population size under investigation.

For the IND method, the mean exposure concentration ΔC_{exp} is replaced by the exposure concentration profile, $C_{exp}(t)$, and the baseline prevalence is expressed in SI units of seconds, $y_{0,s} = y_{0,\text{year}}/(365 * 24 * 60 * 60)$, to obtain the incidence per SI unit of time, $\frac{INC}{time}(t)$ (eq. 4c).

Integration of this function and multiplication with the population size under investigation, pop, leads to the cumulative incidence function $INC(t)$ (eq. 4b).

This number can then be multiplied with the incidence-based DALY factor, $\frac{\partial DALY}{\partial INC}$, to again obtain a cumulative function of DALYs (eq. 4a):

$$DALYs(t) = \left(\frac{\partial DALY}{\partial INC}\right).INC(t) \qquad (4a)$$

$$INC(t) = \int_{t_0}^{t} \left(\frac{INC}{time}\right).pop \qquad (4b)$$

$$\frac{INC}{time}(\text{t}) = -y_{0,\text{s}}.\left[e^{-\beta.C_{exp}(t)} - 1\right] \qquad (4c)$$

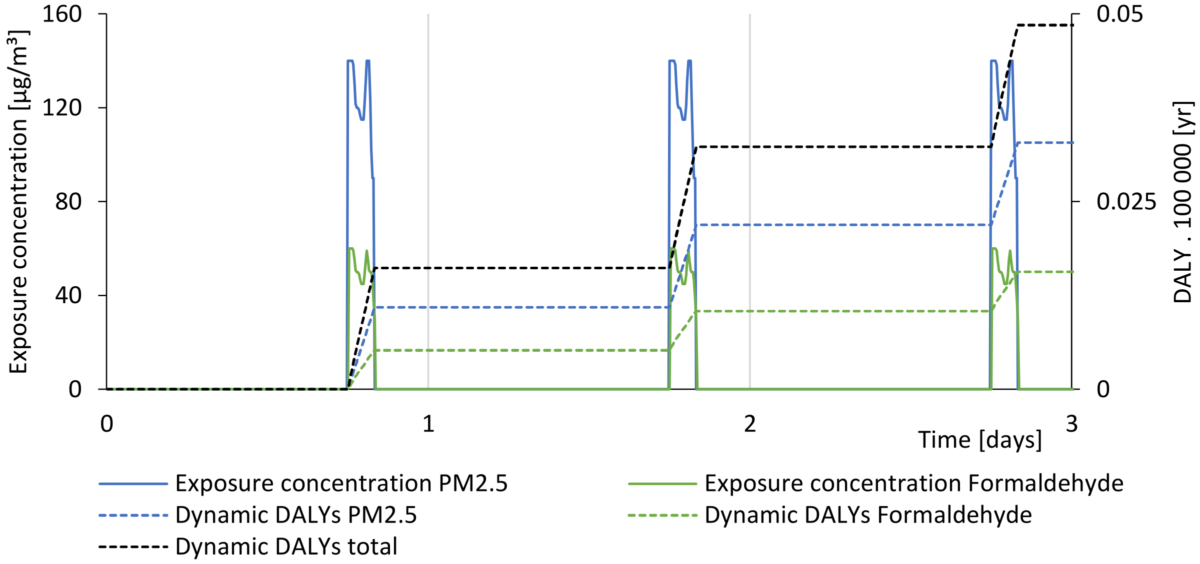

Figure 1 – Plot of the exposure concentration profile of PM2.5 and formaldehyde of the occupant in the theoretical case (solid lines) and the dynamic DALYs related to the exposure to PM2.5 and formaldehyde as well as the total Dynamic DALYs (dotted lines).

To understand the fundamental change in this reformulation, one needs to understand the use of the Logue et. al IND method. To illustrate this, a theoretical, extreme case is used to demonstrate the Logue methods compared to the dynamic DALY methods.

Theoretical case

The exposure profiles for this case and related dynamic DALYs are shown in Figure 1. This is the profile of someone who is only present for two hours a day and during that time he is engaged in a high polluting event (e.g., cooking) without the necessary precautions with regards to IAQ. There is no information available about the exposure outside of his home. Two contaminants are considered in this example, Formaldehyde (Form) and Particulate Matter 2.5 (PM2.5).

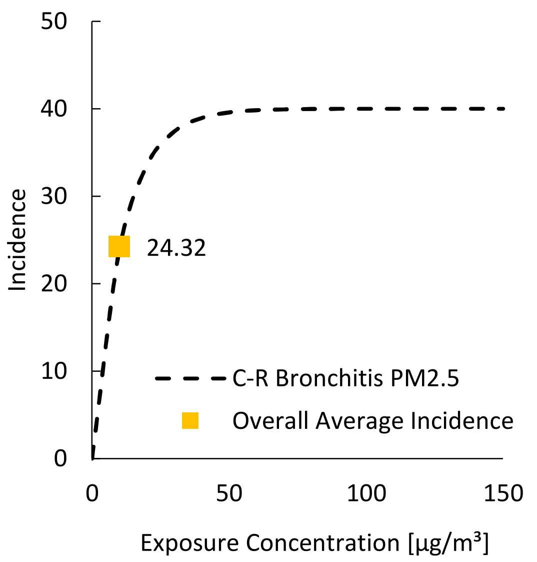

Figure 2 C-R function for chronic bronchitis due to PM2.5 exposure showing a typical non-linear concentration-response relationship.

To quantify the harm due to formaldehyde exposure, the ID method based on toxicological data was applied using the following inputs[14]:

- ADAF=1 [-]
- Inhalation rate, $V_{br}(t)$ = 0.66 m³/h (constant)
- $\frac{\partial DALY_{Cancer}}{\partial intake}$= 7.6e-1 yr/kg
- $\frac{\partial DAL\_nonCancer}{\partial intake}$ = 0 yr/kg

The harm attributed to PM2.5 exposure is calculated using the IND method, for only one health outcome, chronic bronchitis[2] using the following inputs:

- β= 0.091 m³/μg
- $y_{0,year}$= 0.0004 cases/yr
- $\frac{\partial DALY}{\partial INC}$= 1.2 yr/case

A plot of the C-R function used for this example is shown in Figure 2. Note that this C-R function is non-linear which indicates that on a population level, at high PM2.5 exposure concentration levels, an additional rise in exposure concentration level does only cause a slight increase in expected cases of chronic bronchitis.

For both pollutants, first the methods by Logue et. al. were applied for the theoretical case. The steps to be taken to obtain the DALYs using the Logue IND method are shown in Figure 3.

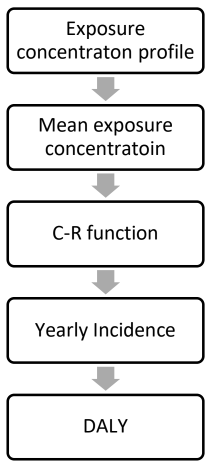

Figure 3 Schematic overview of the step to be taken when applying the Logue IND method starting from detailed exposure concentration data.

Mathematically these steps translate into summarizing the exposure concentration profile into one point and looking for the expected incidence on the C-R function to using this one point (Figure 2). From the incidence, the DALYs can be calculated.

These steps hold two assumptions. The first assumption to use a DALY approach is that one needs to extrapolate the results of one occupant to population size. This assumes that an entire population has the same exposure profile, and that this profile is repeated for a long period of time. The outcome is the response you would expect to see in this population. This assumption is still present in the reformulation and is a key assumption to be mindful about when interpretating the results.

A second assumption embedded in the Logue methods is that the specific highs (peak exposure during events) and lows (well ventilated scenarios close to background concentrations) do not affect the harm to human health differently and thus effectively only the total mass-intake (dose) is of importance. This assumption needs to be made to be able to use the mean exposure concentration ***before*** applying the C-R function.

This is in contrast to the novel dynamic IND approach where it is assumed that the non-linear behavior observed for the long-term health outcomes on a population level is a consequence of a non-linearity in short term micro-physiological responses of different people in the population. This allows the C-R function to be applied ***directly on*** the time-resolved exposure concentration profile. This assumption of micro-physiological response is consistent with research linking elevated levels of biomarkers for e.g. lung inflammation, cardiovascular effects, DNA damage and decreased lung function with increased pollution levels [15–19].

Based on these insights, the assumptions behind the Logue et. al. calculations should not necessarily be regarded as superior to the ones made for the updated method. Nor do we claim the new assumption as superior. There is simply no conclusive evidence for the one or the other at the time of writing and one should be mindful about the difference.

Mathematically the IND reformulation translates into using the C-R function to obtain the expected response from the exposure concentration for every time step of the time-resolved data, for the duration of that time-step, and summating these responses over time. Figure 4 shows the steps embedded in dynamic IND method (equation 4).

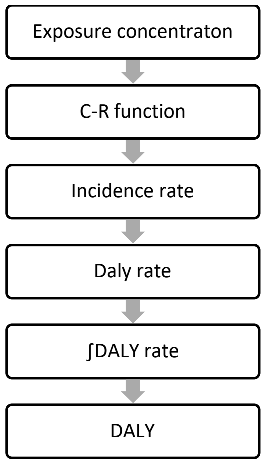

Figure 4 Schematic overview of the step to be taken when applying the dynamic DALY IND method

The different approach with regards to the non-linear C-R function can lead to different overall results. Figure 5 shows the Logue DALY results and dynamic DALY results for the extreme theoretical case, for a year, and illustrates the difference in the IND method results.

If the C-R function used in the IND method is a linear function, this difference would not occur. When comparing the Logue ID method with the dynamic ID method this difference does also not occur due to the linear relationship between exposure, intake and response.

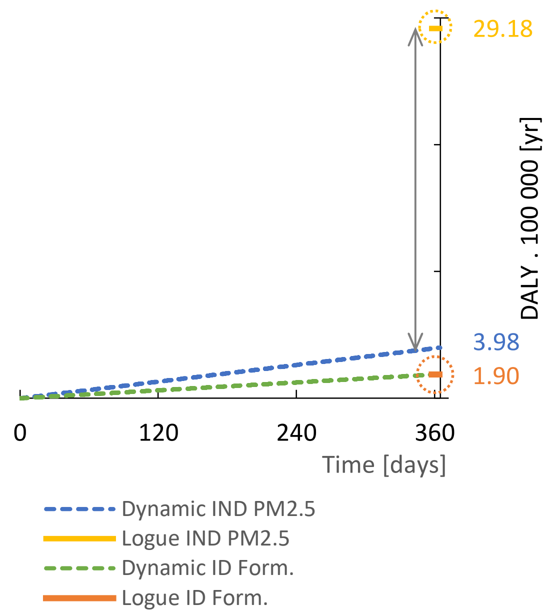

Figure 5 Graph showing the difference or lack in difference in total attributed DALYs over the course of 1 year when applying the Logue IND methods and ID methods respectively for the theoretical case.

Application example: simulation case study

To illustrate the application of this novel method, a simulation case study was conducted using a multi-zone combined thermal and IAQ Modelica model. The modelling was done by use of the IDEAS library[20,21] and proprietary models for interzonal airflow, contaminant sources and occupant exposure. The dynamic DALY output was embedded in the model to evade the need for post-processing.

Building model

The case study is a furnished typical Belgian three-bedroom apartment (Figure 6). This same apartment has been used in studies concerning comfort related IAQ in Belgium[22,23]. The ambient weather represents a typical Belgian year (Uccle). The sources of comfort related contaminants, CO_2 and moisture, are similar as in the models of these previous studies.

Contaminant sources

In addition to sources of CO_2 and humidity included in the reference apartment model[24], contaminant sources of five volatile organic compounds were added:

- Formaldehyde (Form)
- Benzene (Benz)
- Limonene (Limo)
- Naphthalene (Naph)
- Toluene (Tolu)

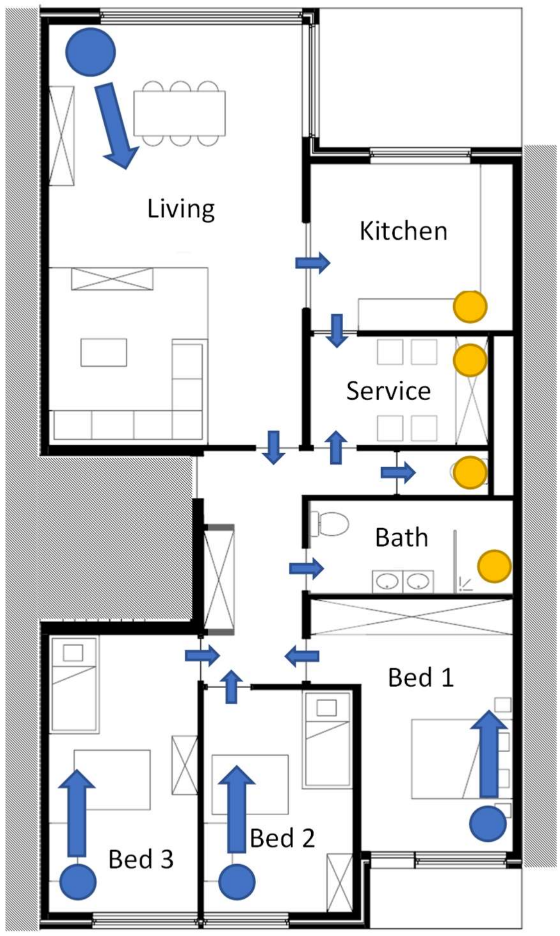

Figure 6 Floorplan of the furnished case study apartment with a schematic overlay of the ventilation system.

This simulation case study focusses on the effect of indoor generated VOCs and did not include contaminants with high background concentration in the outdoor air (e.g., particulate matter (PM), Ozone, NO2)

There are two categories of emission rates considered in this study: emissions from building materials and furniture, and emissions from activities.

The formaldehyde source model for the flooring is a dynamic emission model taking into account the effect of temperature and humidity[25] with a source strength of 9.91µg/h/m³ at 23°C and RH of 50%.

The source strengths of other sources of contaminants are considered constant. The base emission rates are adopted from Ghijsels[26] and shown in Table 1. Based on these emission rates and the sizes of the different furniture in the room, the emission rates for each room were calculated. For each of the VOCs, a constant decay model is used to simulate the effect of these pollutants naturally disappearing due to other mechanisms then ventilation (e.g. secondary reactions, deposition) (Table 1).

Table 1 Fixed furniture and building materials emission rates per unit of exposed surface area and natural decay constants of the VOCs[26].

Emission rates (ug/h/m²)	Form	Benz	Limo	Naph	Tolu
Furniture (Wood)	3.06	1.40	-	5.68	-
Doors (wood)	4.50	-	-	-	-
Cushions	3.00	2.00	-	-	11.00
Carpet	4.27	0.21	-	0.47	0.20
Gypsum	-	-	-	-	0.5
Natural decay constant (1/h)	0	0.05	0.33	0.028	0.015

Table 2 shows the different activities and the respective emission rates considered in this study. The cooktop is not a gas stove, so it was decided to not include formaldehyde emissions from cooking.

Table 2 Activity emission rates

	Limo	Naph
Cleaning	1912 µg/ (h m²)	
Dishes	24.8 µg/h	
Shower *(soap/shampoo)*	1200 µg/h	3.76 µg/h
Deodorant	2000 µg/event	

Four different occupants occupy the apartment:

- 1 Working adult
- 1 Adult staying at home
- 1 Child going to school
- 1 Child staying at home, baby

The occupancy profiles are derived from time-use survey data available at the Belgian National Institute for statistics[27]. This data was used to generate room-based occupancy schedules and the related activities/metabolic rate. Both were implemented in the simulation model using weekly schedules [24,26].

Metric Input

For the considered VOCs in this study, no inputs for the IND method were reported in the paper by Logue et al. Consequently, only the dynamic ID method based on toxicological data was used to calculate the harm for the working adult (ADAF=1). The input values were adopted from Huijbregt et. al.[14] and are summarized in Table 3.

Table 3 Inputs used for the dynamic DALY ID method

Pollutant	$\frac{\partial DALY_{Cancer}}{\partial intake}$	$\frac{\partial DALY_{nonCancer}*}{\partial intake}$
Formaldehyde	7.6e-1	-
Benzene	5.8e-3	3.1e-3
Limonene	3.9e-3	-
Naphthalene	1.1e-2	6.1e-2
Toluene	2.2e-4	4.7e-3

*Noncarcinogenic, Inhalation

Ventilation systems

The ventilation system is a mechanical balanced supply and exhaust ventilation system designed according to the Belgian standard, NBN D50-001[28]. Figure 6 illustrates the positioning of the supply and exhaust vents. The arrows indicate the design flow direction through the apartment.

For this ventilation system two different control strategies are applied. The first system is a continuous ventilation system, continuously supplying and extracting the nominal airflow rate, 100% (Dcont). The second control strategy is a smart ventilation control strategy that uses continuous measurements

Table 4 Description of the control strategy of the smart ventilation system. The airflow rates are expressed in percentage of nominal supply airflow.

	Control parameter	Airflow
Bathroom & Service room	RH < 30%	15%
	30% < RH < 65%	30%
	65% < RH < 95%	60%
	95% < RH	100%
Bathroom	+Δ2% RH in less than 5min (1timestep)	30min at 100%
Toilet	Presence	100%
	No presence < 15min after presence	100%
	No presence > 15min after presence	15%
Kitchen	Δ450ppm < CO_2	15%
	Δ450ppm < CO_2 < Δ550ppm	Linear
	Δ550ppm < CO_2	100%
Livingroom & Bedrooms	Total supply airflow = Total exhaust airflow Flowrates of each supply changed proportionally	15%-100%

of presence, CO_2 and Humidity levels (RH) to optimize the necessary airflow rate, varying between 30% and 100%, to save energy (Dsmart). The ventilation flow rate adjustments are done at each timestep of the simulation. The control strategy of this smart ventilation system is described in Table 4.

Results

As this metric expresses the harmfulness of the exposure concentration it can be used on all contaminants and health outcomes deemed of importance and added together to obtain one quantity that represents the harmfulness of the indoor air. This can be used to extract the moments in time and place where the IAQ management strategy should focus on and which pollutant contributes to the harm the most at this time. Inherent in this metric is the continuous trade-off between concentration levels of different contaminants and the different severity and occurrence of the related health effects.

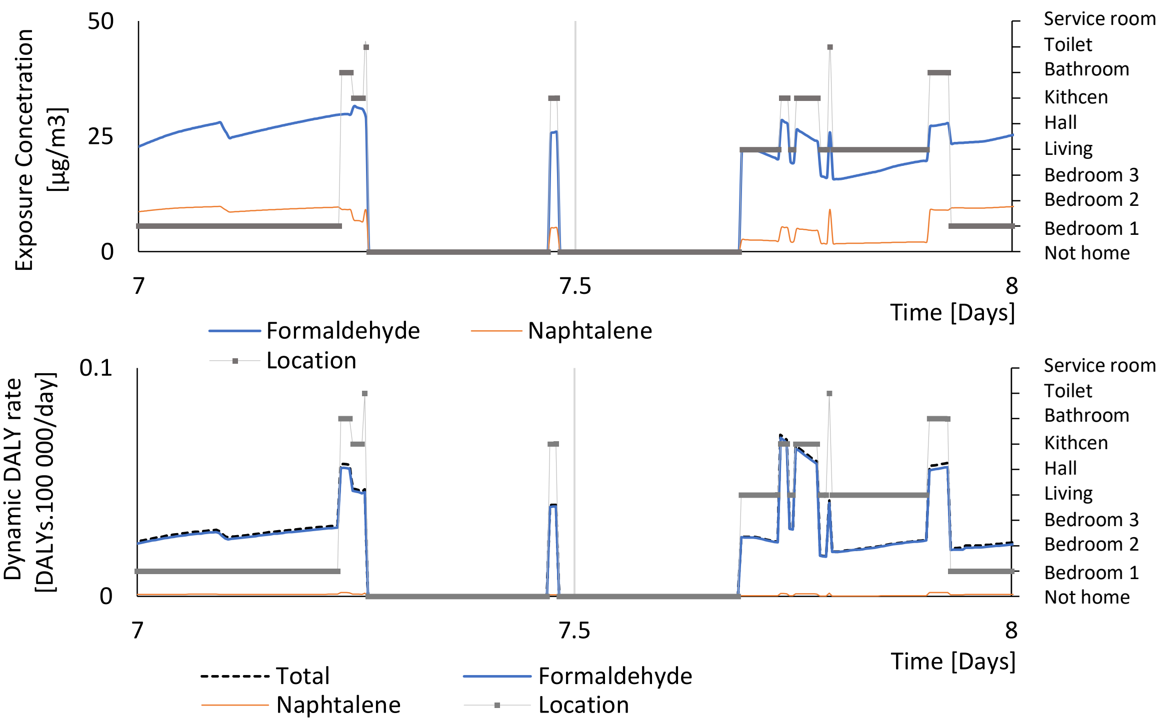

Figure 7 (top) The top graph shows the exposure concentration of the working adult for Formaldehyde and Naphthalene with an indication of the location of this occupant for day 7 of the simulation. (bottom) The bottom graph shows the corresponding Dynamic DALY rate for Formaldehyde and Naphthalene as well as the sum of these two. The harmfulness of Naphthalene is of minimal importance compared to the harmfulness of the Formaldehyde exposure.

Figure 7 illustrates this for two of the pollutants for the smart ventilation case: Formaldehyde and Naphthalene. The top figure shows the exposure concentration of the working adult and the his location. Based on these two concentration profiles and the occupants breathing rate, the Dynamic DALY rate can be computed (3b). This is also equal to the slope of the related cumulative Dynamic DALYs (3a).

A high rate signifies that the indoor air the occupant is exposed to at that time, is more harmful then when the rate is lower. As such, it is a metric for the continuous evaluation of the harmfulness of the indoor air.

The bottom graph in Figure 7 shows this output. It indicates that the contribution of the Naphthalene exposure to the total harm is much lower than the contribution of formaldehyde although the concentration is only approximately 30% lower. It shows that the most harmful air for this day are in the bathroom and kitchen. However, in the spaces where most time is spent (living, bedroom), the air tends to be healthier. The insights in these dynamics is key information in the future development of health-based smart ventilation systems. This output allows to quantify the harmfulness continuously, which makes it a suitable candidate for its use as cost function for the automated optimization of, for example, ventilation system controls using gradient descent optimization methods and/or continuous evaluation of performance in model predictive controls (MPC).

Figure 8 shows the exposure concentration to formaldehyde of the working adult for the second week of the simulated year, for both ventilation systems. It shows that the sometimes-lowered ventilation rates of the smart ventilation system give cause to the indoor formaldehyde to accumulate to higher levels with higher exposures as a consequence. Although it is higher, this does not quantify the rise in harm.

Therefore, the formaldehyde Dynamic DALY output has been calculated and added to the figure, this confirms and quantifies a difference in harm due to the higher exposures.

As expected, the higher exposures cause a faster increase in DALYs. When comparing results on an intermediate scale (e.g., day 10 compared to day 12). The average slope can be used to quantify how harmful a specific day was. As mentioned, the slope of the cumulative Dynamic DALY plot is equal to the Dynamic DALY rate. A steeper slope signifies that the indoor air the occupant is exposed to at that time, is more harmful then when the slope is less steep.

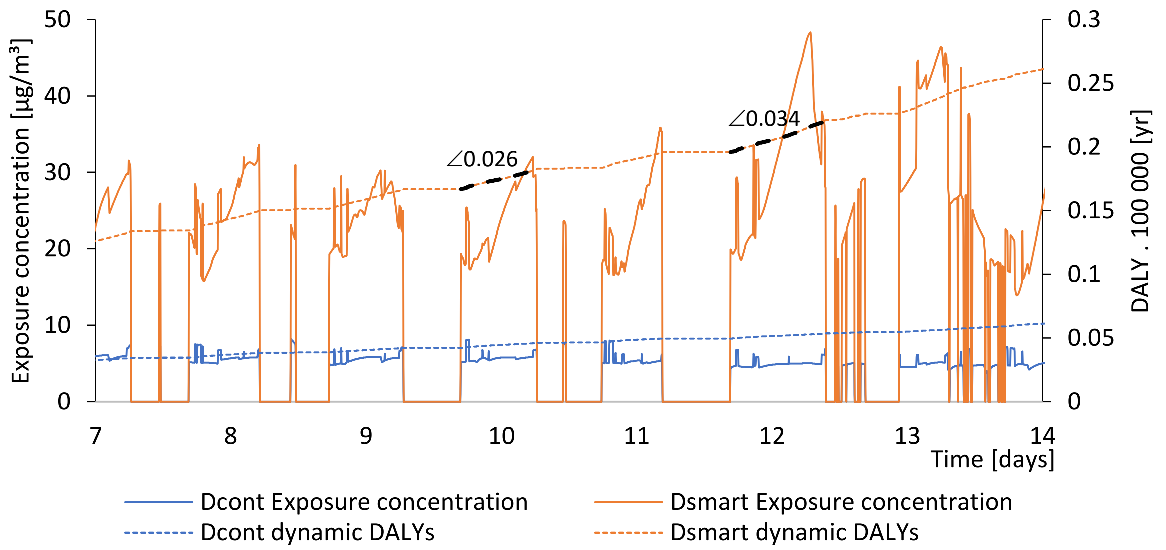

Figure 8 Exposure concentration profile of the working adult, of exposure to formaldehyde for the duration of 1 week (solid lines) and related dynamic DALYs (dotted lines) for Dcont and Dsmart.

It could also be used in a similar way to quantify the contribution of an intervention or for short term harm contribution analysis of events. E.g., A cooking event without a range hood causes 0.05yr/h [DALYs.100 000] during that time, and with range hood only 0.02yr/h [DALYs.100 000].

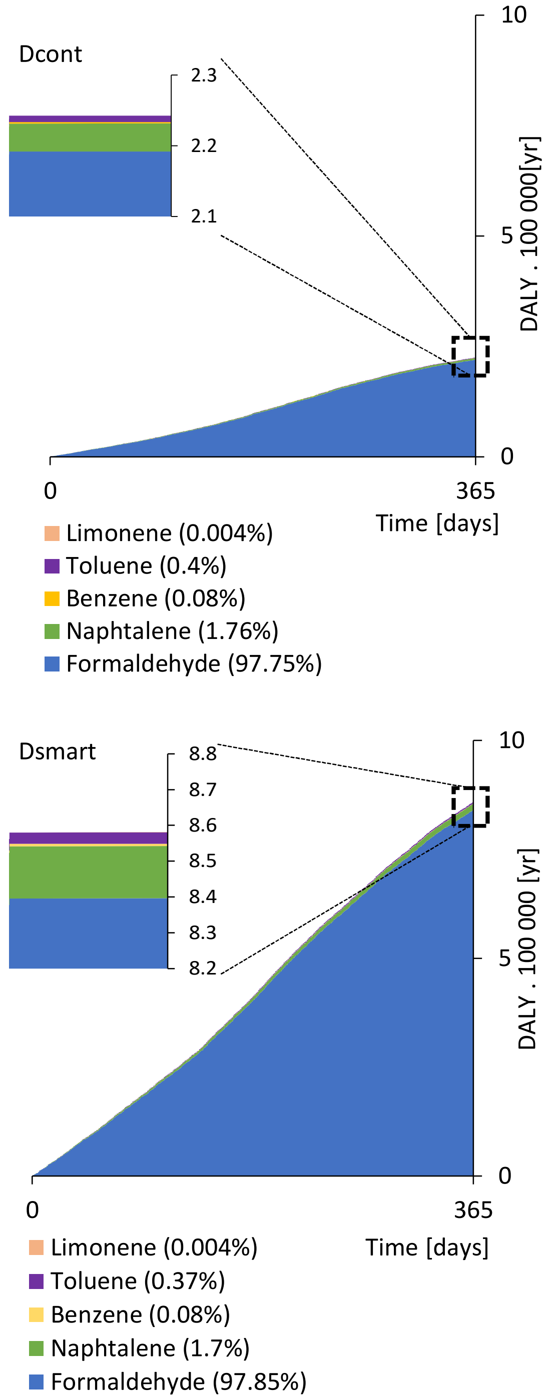

Figure 9 Stacked area plot of the Dynamic DALY output of the working adult for both ventilation systems for the duration of a year. The colors indicate the contribution to harm due to the different VOCs.

Yearly trends

To obtain the total rise in harm due to exposure to all pollutants considered in the simulation, the dynamic DALYs can simply be summed up. A graphic representation of this for the simulated year for both ventilation control strategies is shown in Figure 9.

Note that Formaldehyde accounts for the larger part of the total harm. In both cases more than 97% of the harm can be attributed to formaldehyde exposure. One can see a s- shape in the dynamic DALY curves. This indicates that a bigger portion of the harm was obtained during the summer months. This can be explained by the dynamic formaldehyde emission model of the flooring. The higher temperatures in the summer cause the formaldehyde emissions to be higher, ultimately raising the DALYs at a higher rate during these months. As the harm increases more during these months, the dynamic analysis indicates to act during the summer. For example, adding an additional control algorithm that increases the ventilation rate when temperatures are higher would be able to lower the overall harm while an increase in heating energy use can be avoided. The dynamic character of the output helps to inform decision making for and development of effective IAQ management strategies.

Harm & Energy

Figure 10 shows the total dynamic DALYs for both systems throughout the year and the respective energy use (heating energy use + fan energy use) of the apartment.

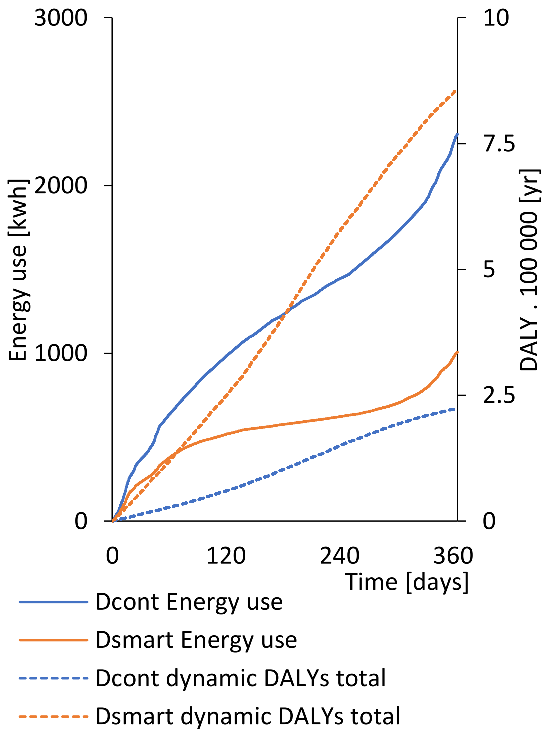

Figure 10 Cumulative plots of the total dynamic DALYs (dotted lines) and building energy use (solid lines).

The value obtained after one full year of simulation are the total yearly DALYs and total yearly energy use. These numbers can be used to summarize the performance of the system. For Dcont the DALYs.100 000 and energy use are 2.2yr and 2307kwh respectively. For Dsmart, the DALYs.100 000 and energy use are 8.6yr and 1008kwh respectively (Figure 11). Or, a 1300kwh energy savings is trade-off with a 6.3yr gain in DALYs.100 000. Whether or not this is acceptable is a societal question for which the answer is not known at the time of writing.

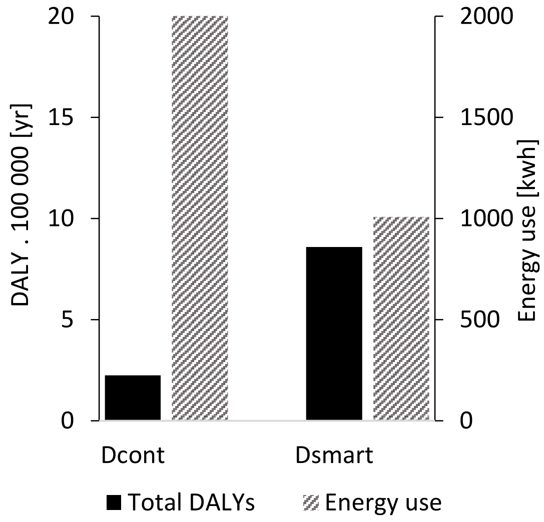

Figure 11 bar-chart showing the overall performance of the two systems over the course of the year with regards to health and energy use.

Conclusions

Dynamic DALYs

A novel method was developed that uses disability adjusted life years, DALYs, to quantify the harmfullness of the indoor air using a time-resolved formulation. These 'Dynamic DALYs' make it possible to use DALYs as a metric when detailed information is available without the loss of information otherwise unavoidable.

This allows the user to analyze the results for different time resolutions (incl. in real-time) ranging from e.g., analyzing the harm due to specific events or presence in a certain room to summarizing the total yearly expected harm using one number.

The application of this method for short term analysis of potential long-term health effects makes it a suitable candidate for pin-pointing problematic events in the exposure profile of an occupant and, as it can be calculated in real-time, makes it a candidate for use in automated optimization problems (e.g., gradient decent optimization or MPC applications).

The applicability of DALYs for state-of-the-art engineering is increased with this method but one should still be mindful about the uncertainties in the calculation of DALYs in general when interpreting the results.

Simulation case study
In the simulation case study, the use of this novel metric was demonstrated. The results show that for the case at hand, the continuously ventilated system (Dcont) provides an overall healthier indoor air to the working adult then the smart ventilation system (Dsmart) would, considering the contaminants in the simulation. Formaldehyde contributes to above 97% of the harm for both investigated ventilation system controls.

Important to note is that the known to be harmful pollutant[2], particulate matter (PM) was not included in this simulation case study. However, as PM typically has a high outdoor concentration as well as important indoor sources and is known to be harmful[2], the inclusion of PM has the potential to weigh in on the results extensively, potentially in favor of the smart ventilation system. To obtain final conclusions about the performance of a smart ventilation system or other IAQ management strategies. The addition of sources of PM is advised.

Perspectives and future applications
The potential applications of being able to quantify the harmfulness of the indoor air in real-time is large.

This new method can for example be used to characterize the harmfulness of a location. Based on the IAQ management strategy, activities and furnishing one could estimate what the rate of DALYs would be and inform the user about how (un)healthy the air is.

E.g. 0.7yr/h [DALY.100 000] in an old office with insufficient ventilation but only 0.2yr/h [DALY.100 000] in a newly built with all new HVAC systems put in place. Building a healthy building with a good IAQ management strategy would then be rewarded.

The same concept can also be applied for outdoor public spaces (roads, parks, subways..) to inform the user to take the healthiest route from point A to B. Similar to a navigation app that redirects the route if a better, alternative route becomes available.

Combined with sensors, this information can be updated real-time and daily/yearly trends in harmfulness can be recognized and then, if necessary, mitigated.

Smart ventilation systems can use the information of contaminant sensor arrays to weigh off conflicting effects of increasing ventilation flow rates. E.g. when the outdoor air is polluted with PM, it might be better to ventilate less but only to the point where indoor generated formaldehyde concentration levels do not rise to equally harmful levels.

Conflict of interest statement
No conflict of interest declared.

Data Availability Statement
The data that support the findings of this study are available from the corresponding author upon reasonable request

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