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The microenvironmental modelling approach to assess children's exposure to air pollution - a review

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Abstract

Exposures to a wide spectrum of air pollutants were associated to several effects on children's health. Exposure assessment can be used to establish where and how air pollutants' exposures occur. However, a realistic estimation of children's exposures to air pollution is usually a great ethics challenge, especially for young children, because they cannot intentionally be exposed to contaminants and according to Helsinki declaration, they are not old enough to make a decision on their participation. Additionally, using adult surrogates introduces bias, since time-space-activity patterns are different from those of children. From all the different available approaches for exposure assessment, the microenvironmental (ME) modelling (indirect approach, where personal exposures are estimated or predicted from microenvironment measurements combined with time-activity data) seemed to be the best to assess children's exposure to air pollution as it takes into account the varying levels of pollution to which an individual is exposed during the course of the day, it is faster and less expensive. Thus, this review aimed to explore the use of the ME modelling approach methodology to assess children's exposure to air pollution. To meet this goal, a total of 152 articles, published since 2002, were identified and titles and abstracts were scanned for relevance. After exclusions, 26 articles were fully reviewed and main characteristics were detailed, namely: i) study design and outcomes, including location, study population, calendar time, pollutants analysed and purpose; and ii) data collection, including time-activity patterns (methods of collection, record time and key elements) and pollution measurements (microenvironments, methods of collection and duration and time resolution). The reviewed studies were from different parts of the world, confirming the worldwide application, and mostly cross-sectional. Longitudinal studies were also found enhancing the applicability of this approach. The application of this methodology on children is different from that on adults because of data collection, namely the methods used for collecting time-activity patterns must be different and the time-activity patterns are itself different, which leads to select different microenvironments to the data collection of pollutants' concentrations. The most used methods to gather information on time-activity patterns were questionnaires and diaries, and the main microenvironments considered were home and school (indoors and outdoors). Although the ME modelling approach in studies to assess children's exposure to air pollution is highly encouraged, a validation process is needed, due to the uncertainties associated with the application of this approach.

Keywords: Exposure modelling; air pollution; children; microenvironments

Conflict of interests

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1. Introduction

1.1. Relevance of the assessment of children's exposure to air pollution

Duan (1982) and Ott (1982) introduced in the early 80's the concept of *human exposure* (or simply *exposure*), which was defined as "an event that occurs when a person comes in contact with the pollutant" (Ott, 1982). Thus, exposure to air pollution occurs whenever a human being breathes air in a location where there are at least trace amounts of airborne pollutants (Klepeis, 2006). Although the first official efforts to control air pollution have traditionally focused on outdoor air, it is now apparent that elevated contaminant concentrations are common inside both private and public buildings (Spengler and Sexton, 1983). Attention should continue to be paid to outdoor air quality and its influence on human health, especially in urban and/or industrialized areas of developed countries. However, people spend up to 90% of their time indoors, making indoor air quality more important than outdoors (Harrison, 1997). Whilst this does not *per se* mean that indoor exposures will produce more harmful effects, the evidence is that indoor concentrations of many pollutants are often higher than those typically encountered outside (Jones, 1999; Sousa et al., 2012a).

Children are highly vulnerable to air environmental hazards, being considered a risk group (Nieuwenhuijsen et al., 2006; Peled, 2011; Sousa et al., 2009, Sousa et al., 2012b, Sousa et al., 2013) for several reasons including their relative higher amount of air inhalation (the air intake per weight unit in a resting infant is twice than in an adult) and their not fully developed immune system and lungs. As above referred, evidence has been made that children, as well as adults, spend most of their time in indoor environments and are therefore more exposed to indoor air pollution. As a consequence, exposures to a wide spectrum of air pollutants were associated to several effects on children's health, like the increasing of the occurrence of asthma, other allergies and respiratory diseases (Hulin et al., 2010; McGwin et al., 2010; Mendell, 2007; Rumchev et al., 2002; Salvi, 2007; Schwartz, 2004; Sousa et al., 2012a). Evidences of other health outcomes have been found: i) Brook et al. (2004) and the World Health Organization (WHO, 2006) reported cardiovascular diseases associated with exposure to air pollutants; and ii) a review from Beamish et al. (2011) suggested that there is a link between air pollution and intestinal disease.

In their daily routine, children move from one location to another and are exposed to a large number of air contaminants for different time durations, raising serious questions about whether such exposures are likely to cause adverse health effects, and what are pollutants' sources. Thus, a complex multifactorial approach for exposure assessment seems appropriate aiming to: i) associate exposure with health effects; ii) link health effects with pollution sources; and iii) determine the exposure value of an individual or group of individuals relative to the population exposure distribution (Moschandreas and Saksena, 2002). In this field, epidemiologic studies provide the opportunity to assess the effects of exposure to air pollution on children's health, i.e., the exposure-response relationship. Multiple outcomes from this type of studies are of interest (Gilliland et al., 2005), including the prevalence of asthma and respiratory diseases, as well as the associated morbidity and mortality. In several countries, as the example of China (Ye et al., 2007), despite the increasing concern about environmental health, most risk-assessment activities are conducted focusing on adults, making environmental health policies inefficient in protecting children's health. Children exposure should be developed to characterize real-life situations, whereby i) potentially exposed populations are identified; ii) potential pathways of exposure are identified; and iii) the magnitude, frequency, duration and time-pattern of contact with a pollutant are quantified (Hubal et al., 2000). Assessing children's exposure to air pollution cannot be merely reduced to the measurements of air pollutants concentrations in one or more environments. In fact, exposure studies can be used to establish where air pollutants exposures occur and the source of those air pollutants (Weisel, 2002).

Hubal et al. (2000) reviewed the factors that strongly influence children's exposure, and concluded that: i) the physiologic characteristics and behavioural patterns of children result not only in exposure differences between children and adults, but also in differences in exposures among children of different developmental stages; ii) significant challenges are associated with developing and verifying exposure factors for young children, so it is necessary to develop and improve the methods for monitoring children's exposures and activities; iii) the data usually available for conducting children's exposure assessments are highly variable, depending on the route of exposure considered, so it requires the collection of physical activity data for children (especially young children) to assess exposure by all routes. Socioeconomic status also greatly influence children's exposure to air pollution (Chaix et al., 2006).

1.2. Methods to assess children's exposure to air pollution - main advantages and limitations

The study of exposure assessment has evolved significantly over the past 30 years (Lioy, 2010) through the appearance of a myriad of methods for assessing personal exposure levels to air pollution. Two different approaches, direct and indirect, described below, have been taken to assess personal exposure to air pollution (Ott, 1982).

There are two available direct methods: i) personal monitoring, which monitors pollution concentrations using portable equipment worn by the subjects, which can work actively (pumped) or passively (diffusive); and ii) biomonitoring, which is the use of biomarkers to assess exposure to air pollution, although its usability on exposure studies to air pollution is very specific. Simplicity of design and freedom from modelling assumptions are the advantages of the direct approach (Duan et al., 1991; Wallace and Ott, 1982). Despite direct measurements clearly reflect individual personal exposure levels best, measurements of personal exposures are expensive, time consuming and difficult to apply (Monn, 2001), especially to young children (Jones et al., 2007). It is important to note that a personal measurement does not *a priori* provide more valid data than a stationary measurement, i.e. a personal sample in a study investigating effects from a specific place or source is often influenced by other sources than those on focus of the investigation, and may thus confound the exposure-effect outcome. Nevertheless, in 1984 EPA performed two large studies of carbon monoxide (CO) exposure in Washington, DC and Denver Colorado, where 1987 persons were followed for 24 hours in DC and 1139 persons were followed for two days in Denver. The specific personal monitor used provided exact times in each microenvironment without having to write them down in a questionnaire. This was the first and the most complete study to ever include actual ME measurements, and included many more MEs than in subsequent studies, although being a personal monitoring study (Akland, 1985). While biomarkers offer clear advantages, some important criteria must be met when using them for this purpose (Hubal et al., 2000): i) biomarkers that can accurately quantify the concentration of an environmental contaminant and/or its metabolite(s) in easily accessible biological media (blood, urine, and breath) must be available; ii) biomarkers must be specific to the contaminant of interest; iii) the pharmacokinetics of absorption, metabolism, and excretion must be known; and iv) the time between exposure and biomarkers sample collection must be known. Although there are a number of biomarkers that meet these criteria, few studies using biomarkers have collected all of the information required to accurately estimate exposure. In studies with large sample sizes, long duration and diverse outcomes and exposures, exposure assessment efforts should rely on modelling to provide estimates for the entire cohort, supported by subject-derived questionnaire data, although assessment of some exposures of interest requires individual measurements of exposures using snapshots of personal and microenvironmental exposures over short periods and/or in selected microenvironments (Gilliland et al., 2005). In addition, significant challenges are associated with collecting biomarkers' data from children (Weaver et al., 1998). Although findings from Sexton et al. (2000) indicated that, with proper care, it could be practicable to obtain personal volatile organic compounds (VOC) measurements from elementary school children wearing personal VOC badges samplers, direct methods are unusual on children studies due to their difficult applicability on their time-space-activity specifications. For example, personal monitors for suspended particles (PM) may be particularly impractical for infants or young children due to the requirement of attached pumps (Jones et al., 2007).

Exposure modelling is the indirect method that assesses (estimates or predicts) personal exposures derived from ambient measurements (i.e., measurements made in locations frequented by the study participants) combined with time-activity data, which results in exposure models (MacIntosh and Spengler, 2000; Monn, 2001; Ott, 1982). Some authors reviewed the existing exposure models and tried to classify them, by dividing them into different categories, like Klepeis (2006) and Zou et al. (2009), but the most common classification is into three major groups, as recently reviewed by Milner et al. (2011): i) Statistical Regression models (not unanimously considered as models), in which linear and nonlinear regression techniques are used to relate personal exposure to its determinants based on measurement data (Kollander, 1991); ii) Computational Fluid Dynamics (CFD), used to model the spatial and temporal variations in pollutants' concentrations at an extremely fine scale, working on the basic fluid dynamics principles; and iii) Microenvironmental (ME) modelling, an approach in which weighted average exposure is calculated using time spent and time-averaged concentrations at various places where the population under observation is likely to circulate (Duan, 1981; 1975). There are also examples where different models can be complementary (Mölter et al., 2010a; Mölter et al., 2010b), increasing the amount of available data for assessing personal exposure to air pollution, or using both indirect and direct approach to compare the exposure values estimated by the indirect approach with the real personal sampling measured values, which can also be done to validate the model.. It is feasible to believe that the indirect methods of exposure assessment can yield estimates closely matching those of the direct method (Malhotra et al., 2000). However, CFD is not considered appropriate for generic population exposure modelling, because it is primarily a research tool used for ventilation, air flow and contaminants' modelling, rather than individual or population exposure modelling. In the same way, and despite being frequently used in epidemiologic studies, regression models have major issues that could be constraints to their applicability, like their transferability to other locations and to other periods of time, when compared to a mechanistic approach like ME modelling (Ashmore and Dimitroulopoulou, 2009). In this field, ME modelling can be used to determine exposures to both individuals and large populations, because it is not often financially practical to make a sufficient number of exposure measurements to completely characterize the spatial and temporal range of exposures in large populations, and to predict what changes in emissions or activities are most effective to obtain reduced exposure (Weisel, 2002). Furthermore, it has several advantages, mainly the possibility to be rapidly and inexpensively used to calculate estimates of exposure over a wide range of exposure scenarios (Klepeis, 1999), and it is also the most appropriate way to examine the potential outcomes of future environmental and/or building interventions and policies, safeguarding the importance to consider indoor exposure modelling (Milner et al., 2011). However, and according to Klepeis (1999), a main disadvantage of this approach compared to the direct approach is the currently research need for its systematic validation, i.e., the results of a fully developed indirect exposure assessment must be compared to an independent set of directly measured exposure levels. The main advantages and limitations of the methods and approaches available to assess children's exposure to air pollution, as well as several examples of studies using them, are summarized in Table 1.

1.3. Scope and objectives of this review

Exposure studies on children are usually a great ethics challenge especially for young children, because they cannot intentionally be exposed to contaminants and according to Helsinki declaration, they are not old enough to make a decision on their participation. Using adult surrogates for these studies introduce bias, because adults do not behave like young children, therefore they cannot mimic their contact activities (Hubal et al., 2000). This is why it is a challenge to develop a realistic estimation of children's exposures to air pollution.

Despite the several available methods within different approaches to assess human exposure to air pollution, the ME exposure modelling method seemed to have several advantages and a great application potential to the assessment of children's exposure to air pollution. With the time children spend in each location (microenvironment) and time-averaged pollutant concentrations, it is possible to estimate and quantify the exposure distribution of study subjects. Additionally, it is viable to examine the likely influence of each location and other exposure factors (Klepeis, 2006). Since children's time-space-activity patterns are different from those of adults, the performance of this modelling approach in estimating personal exposures may differ between these two different types of population (Wu et al., 2005a). Thus, this review aimed to explore the ME modelling approach methodology to assess children's exposure to air pollution. To meet this goal, this work reviewed studies from the last decade on the assessment of children's exposure to air pollution using this approach, focusing on the methodology, challenges and limitations, to provide a summary of the available scientific findings concerning study design and data collection (time-activity patterns information, microenvironments' selection and pollution measurements), and to some extent look at the outcomes and ME model type.

2. Methodology of this review

The present review refers to articles published from 2002 to date in the following on-line databases: *Science Direct*, *Scopus*, *PubMed* and *Google Scholar*. Although no restrictive criterion was established to limit the language in which the articles were published, all the citations refer to documents published in English. The search considered only fully published and in press articles.

This review was elaborated to report original research and review studies on the assessment of exposure in several microenvironments, with children as the main population study and/or as one of the study sub-groups, and focusing on those using ME modelling approach to assess children's exposure to air pollution. Thus, the main keywords used for the search were: "children's exposure", "air pollution", "assessment", "microenvironment", and "modelling". A total of 152 articles were identified and titles and abstracts were scanned for relevance. Detailed exposure measurement or estimation methodologies and models on different approaches are beyond the scope of this review, and can be found reviewed in other papers (Baxter et al., 2013; Klepeis, 2006; Milner et al., 2011; Moschandreas et al., 2002; Steinle et al., 2013). The type of article, i.e. being an original, review, letter or other type, was not used as inclusion or exclusion criteria due to the limited number of articles that addressed this topic.

Exclusions were performed, namely regarding those studies that: i) did not consider children as the population study or as one of the population sub-groups; ii) studies that did not used ME modelling approach to assess exposure to air pollution; iii) only considered a unique microenvironment; and iv) merely focused on the conceptual framework or only on one of the ME modelling aspects.

Studies that relied on both indirect and direct methods for their exposure assessments were also included. After exclusions, the search performed retrieved 26 articles containing studies on the assessment of children's exposure to air pollution using a ME modelling approach.

3. Results

3.1. Conceptual framework

In daily life, people move around and thus are exposed to various levels of pollutants in various locations. The earlier researchers Fugas (1975), Duan (1981, 1982), and Ott (1982) introduced the concept of calculating exposure as the sum of the product of time spent by a person in different microenvironments and the time-averaged air pollution concentrations occurring in those microenvironments. Equation (1) represents the standard mathematical formula for integrated exposure.

$$E_i = \sum_{j=1}^{m} C_{ij} t_{ij} \quad (1)$$

E_i is the exposure of the *i*th individual, C_{ij} is the concentration of the pollutant measured in the *j*th microenvironment of the *i*th individual, t_{ij} is the time spent by the *i*th individual in the *j*th microenvironment, and *m* is the number of different microenvironments, such that the Equation 2 is satisfied:

$$\sum_{j=1}^{m} t_{ij} = 24h \quad (2)$$

In a review, Milner et al. (2011) distinguished the following types of ME models: i) measurement-based ME models, based on observational (measured) data, usually long-term averages, whether from air quality monitoring stations or local outdoor or indoor measurements; ii) mass-balance ME models, which model the movement of air pollution throughout a system of one or two ME compartments and from outdoors based on principles of mass conservation; iii) multizone ME models, based on the same principles as mass-balance ME models, although in this case a larger number of microenvironments are modelled, with exceptionally detailed input data requirements; and iv) sub-zonal ME models, similar to multizone but additional sub-zones are considered to capture within-room gradients, being useful for buildings/rooms which may have high gradients of concentration.

By using a ME exposure model, the researcher in each case can quantify the exposure distribution of study subjects and examine the likely influence of each location and other exposure factors (Klepeis, 2006). When the required input data are available or can be reliably estimated, the target population exposure distributions can be predicted accurately enough for the most practical purposes using a ME modelling approach (Hänninen et al., 2003).

Time-activity patterns are an important determinant of personal exposure to air pollution and crucial in ME modelling exposure, not only because of the time spent on those microenvironments but also because: i) personal exposure to environmental toxics is largely dependent on the movement across locations or microenvironments; and ii) of the different contributions of microenvironments on specific population groups (Dons et al., 2011). Therefore, time spent in different microenvironments makes a significant contribution to the total exposure. Regarding children, differences in their behaviour, particularly the way in which children interact with their environment, may have a profound effect on the magnitude of exposures to contaminants. In fact, the manner in which children, and in special infants and toddlers, move is significantly different from the manner in which adults move and can significantly impact their exposure to contaminants in the air (Hubal et al., 2000). Plus, socio-demographic and environmental factors define time-activity patterns and also define quantifiable differences in personal exposures to different sources and individual compounds (Edwards et al., 2006). These and other determinants of time-microenvironmental-activity patterns need to be taken into account in exposure assessment, epidemiological analyses, and exposure simulations, as well as in the development of preventive strategies that focus on time-microenvironment-activity patterns that ultimately determine exposures (Schweizer et al., 2007).

The main characteristics of the ME modelling approach to assess children's exposure to air pollution in the 26 reviewed studies are listed in: i) Table 2, regarding study design and outcomes, namely location, study population, calendar time, pollutants analysed, purpose and type of study; and ii) Table 3, regarding data collection, namely time-activity patterns (including methods of collection, record time and key elements included), and pollution measurements (including microenvironments, methods of collection and duration and time resolution).

3.2. Study design and outcomes

Any exposure research should start by planning the design: purpose and objective, study population, pollutants analysed, temporal and spatial resolution, type of study as well as outcomes. It is possible to observe from Table 2 that eleven of the reviewed studies were performed in the USA, but there were also studies performed in Europe, Australia, Latin America, India and Asia.

The majority of the selected studies had the assessment of children's exposure to air pollution as main purpose, and in some cases relating it with adverse health effects. Some of those studies also aimed to compare children's exposure between different areas of the same city or region like urban vs. suburban; influence from streets with different degrees of traffic intensity, or between cities from different countries (Ballesta et al., 2006; Shimada and Matsuoka, 2011; Mestl et al., 2006; Van Roosbroeck et al., 2007; Van Roosbroeck et al., 2006).

In the majority of the reviewed studies the calendar time was described, although in some it was not reported (Harrison et al., 2002; Rojas-Bracho et al., 2002; Shimada and Matsuoka, 2011; Mestl et al., 2006; Van Roosbroeck et al., 2007; Wu et al., 2005b; Zhang and Batterman, 2009). The reviewed studies were published since 2002 and in some cases there was a gap between the period when the study took part and its publication date, as for example in Crist et al. (2008) where this gap was more than 8 years.

The overwhelming majority of the reviewed studies were cross-sectional, and only 3 were longitudinal: i) a cohort study where children's exposure was estimated and health outcomes were evaluated every year from age one until the age three (Ryan et al., 2008); ii) a panel study involving repeated measurements of outcomes and exposures in individuals (Wu et al., 2005a); and iii) a panel study conducted in several different monitoring sessions in each one of the two consecutive years (Liu et al., 2003).

The reviewed studies considered children from birth (Hänninen et al., 2009; Ryan et al., 2008; Shimada and Matsuoka, 2011; Mestl et al., 2006; Wang et al., 2008), to schoolchildren with ages comprised between 5 and 14 years old (Briggs et al., 2003; Mölter et al., 2012; Zhao et al., 2007), although, in some of them children were a subgroup of the entire study population (Ballesta et al., 2006; Briggs et al., 2003; Chau et al., 2002; Harrison et al., 2002; Liu et al., 2003; Shimada and Matsuoka, 2011; Mestl et al., 2006; Wheeler et al., 2011; Zhang and Batterman, 2009). In the latter studies, a stratified sampling was used, despite the study population selection was normally done by a probability sample – children were normally selected on a school-based strategy, thus recruited from schools. Nevertheless, Wu et al. (2005b), Adgate et al. (2004b) and Saksena et al. (2003) recruited children based on a probability sample of households, and Wheeler et al. (2011) recruited study participants from a previous study. In the particular cases of Liu et al. (2003) and Yip et al. (2004), only children aged 7-11 with known or probable asthma were selected from the general population, thus not using a probability sampling.

Exposures to a wide spectrum of environmental pollutants were considered for investigation in the studies selected, including air pollutants of indoor and outdoor origin, gaseous compounds and/or particles. Nevertheless, in all studies reviewed and presented in Table 2, the pollutants analysed were mainly combustion-related, with the exceptions of ozone in Lee et al. (2004), and radon in Briggs et al. (2003). Additionally, no examples were found of the application of ME modelling approach to study children's exposure to biological compounds, like aeropathogens, moulds and allergens.

Regarding the outcomes which are deeply related with the purpose and objectives of the study, the reviewed studies were mostly in the field of the characterization of children's personal exposures and their relation with outdoor and indoor concentrations (Table 2). A common conclusion in the reviewed studies was the significant importance of air quality in indoor microenvironments to children's exposure to air pollution.

3.3. Data collection

3.3.1.Time-activity patterns information

The reviewed studies mainly used a time-activity diary as method for collecting time-activity patterns (Table 3). A questionnaire or information from previous studies or existing databases were also used in some cases (Shimada and Matsuoka, 2011; Mestl et al., 2006; Zhang and Batterman, 2009) to collect time-activity patterns information. Crist et al. (2008) and Zhao et al. (2007) did not report the methods of collection used. Chau et al. (2002) and Lee et al. (2004) used diaries and questionnaires done by telephone surveys to the parents. To support survey's information in a study from Italy (Hänninen et al., 2009), time-activity patterns information was also derived from school administration and using typical daily timetables of schoolchildren. In the study of Wu et al. (2005a) participants used an electronic time-activity diary.

Time-activity patterns information were usually recorded in a daily basis (24-h recordings), although Ryan et al. (2008) reported one complete year (12 months) and Chau et al. (2002) and Wang et al. (2008) a 7-day period. On the other hand, a shorter period was also found in Lee et al. (2004), with a specific period of the day (from 8:00 a.m. to 9:00 p.m.). The most common time-interval found was 15-min, but different time-intervals were also found. Wheeler et al. (2011) and Briggs et al. (2003) used 30-min intervals to record time-activity patterns information for children.

Additional information on microenvironments' characteristics (Lazenby et al., 2012; Mölter et al., 2012), possible indoor sources (Liu et al., 2003; Van Roosbroeck et al., 2007; Van Roosbroeck et al., 2006), data on exposure to tobacco smoke and other potential modifiers (Adgate et al., 2004a; Adgate et al., 2004b; Rojas-Bracho et al., 2002; Wheeler et al., 2011), basic socio-demographic and/or socioeconomic data (Chau et al., 2002; Zhang and Batterman, 2009), and health information (Ryan et al., 2008) were also often collected.

3.3.2. Pollution measurements

All the reviewed studies chose the specific microenvironments for pollution measurements according to the time-activity information collected (Table 3). They considered mostly both outdoor and indoor (home and school) microenvironments, although some studies also considered in traffic (Adgate et al., 2004b; Hänninen et al., 2009; Mölter et al., 2012; Rojas-Bracho et al., 2002; Wang et al., 2008; Wheeler et al., 2011; Wu et al., 2005a; Wu et al., 2005b; Zhang and Batterman, 2009). Crist et al. (2008), Zhao et al. (2007), Van Roosbroeck et al. (2007) and Lee et al. (2004) had only school indoor and outdoor as the unique studied microenvironments, and Briggs et al. (2003) did the same but for home. Mölter et al. (2012), Shimada and Matsuoka (2011), and Wang et al. (2008) went further in the analysis and divided home indoors into different microenvironments, like kitchen, living room and children's bedroom. Also Crist et al. (2008) and Adgate et al. (2004a) have considered different microenvironments in school indoors (different classrooms). Chau et al. (2002) and Harrison et al. (2002) sub-divided the main microenvironments according to time-activity patterns information collected. Ryan et al. (2008) considered home and non-home (including daycare, babysitter, relative's home and other locations). Chau et al. (2002) considered a higher number of microenvironments (20), but grouped them into indoor at home, indoor away from home, enclosed traffic and outdoor. Some regular activities were also considered as microenvironments in some cases, as the example of cooking and sleeping sessions (Saksena et al., 2003) and leisure activities (Harrison et al., 2002).

Data availability and its quality for model input are critically important, so distinct methods of collection were found in the 26 reviewed studies (Table 3), mainly depending on the microenvironments analysed. Outdoor concentrations were often obtained through continuous measurements from the nearest urban monitoring air quality station (Hänninen et al., 2009; Mölter et al., 2012; Wang et al., 2008; Wu et al., 2005a), or with the support of dispersion models (Ryan et al., 2008; Mestl et al., 2006; Wu et al., 2005b). In some studies, indoor concentrations were obtained from continuous measurements in the indoor microenvironments (Adgate et al., 2004a; Briggs et al., 2003; Harrison et al., 2002; Wheeler et al., 2011). In other cases, personal individual monitoring was performed in indoor microenvironments instead of indoor ME measurements (Van Roosbroeck et al., 2007; Van Roosbroeck et al., 2006). Indoor concentrations were also estimated i) through the use of modelling, mainly mass-balance or infiltration models (Hänninen et al., 2009; Wu et al., 2005b); or ii) from the fuel consumption and room characteristics (Shimada and Matsuoka, 2011); or iii) estimated based on data from databases or previous studies in the literature (Chau et al., 2002; Mestl et al., 2006; Zhang and Batterman, 2009). Passive or diffusive sampling was also found as a method to collect pollution measurements in the reviewed studies, mainly to obtain indoor ME concentrations (Adgate et al., 2004b; Ballesta et al., 2006; Lazenby et al., 2012; Rojas-Bracho et al., 2002). Lazenby et al. (2012), Mölter et al. (2012), Van Roosbroeck et al. (2006) and Wu et al. (2005b) also collected general meteorological data. A different method to measure the pollutants concentrations was performed by Lee et al. (2004), in which each participating child and family had a set of personal (wearable) / indoor / outdoor passive O_3 samplers. Other cases exist in which a personal individual sampler was also used, particularly to compare with the ME concentrations measured indoor and/or outdoor (Crist et al., 2008; Liu et al., 2003; Mölter et al., 2012; Yip et al., 2004). In fact, Mölter et al. (2012) proposed a simple validation process in their ME model, by comparing the modelled with the measured personal exposure results, which allowed to understand if, by using a ME exposure modelling approach, the modelled values estimated the children's personal exposure to air pollution with efficiency. Besides pollutants' concentrations, the ME model proposed by Adgate et al. (2004a) also included singular characteristics of the microenvironments as covariates, like for example the "design" (season, English or non-English-speaking home, race/ethnicity, and level of education), source variables (e.g., presence of a smoker in household), and ventilation.

The duration and time resolution of pollution measurements were found to be variable within the reviewed studies (Table 3). In fact, it varied from periods of 24 and/or 48 hours of measurements (Crist et al., 2008; Lazenby et al., 2012; Rojas-Bracho et al., 2002; Saksena et al., 2003; Van Roosbroeck et al., 2007; Wang et al., 2008; Zhao et al., 2007) to periods of several weeks (Briggs et al., 2003; Lee et al., 2004; Wheeler et al., 2011) or even an entire school year of measurements (Hänninen et al., 2009). In some cases, different measurement periods or campaigns were considered (Ballesta et al., 2006; Liu et al., 2003; Van Roosbroeck et al., 2006), and in some of them measurement campaigns were made in different seasons to study seasonal variability (Adgate et al., 2004a; Mölter et al., 2012; Wheeler et al., 2011; Yip et al., 2004).

4. Discussion

There is no universal methodology to use a ME modelling approach to assess children's exposure to air pollution. In addition, there is evidence that usually a methodology developed for a certain exposure study is very specific for that particular purpose, objectives, and mainly for that study group or population, and for that spatial and temporal context. This makes the studies' methodology harder to extrapolate to other contexts, and consequently makes the studies' comparison tricky. Unfortunately, most of the studies in the literature are focused on adult subjects. Since children's time-space-activity patterns are different from those of adults, the performance of this modelling approach in estimating personal exposures may differ between these two different types of population (Wu et al., 2005a). Nevertheless, 26 studies were reviewed using a ME modelling approach to assess children's exposure to air pollution, from different countries, which enhances the possibility of a worldwide application of this approach.

In the majority of the studies reviewed, children were selected through a probability sample, and in some cases a stratified sampling was also used. This does not imply any escape from probability selection but a better precision, because it ensures that subgroups of the population will be included in the sample to maximize the accuracy of the study (Kollander, 1991). One potentially successful design strategy is to maximize the number of contrasting pollution profiles among study subjects by using a quasi-factorial approach to select populations distributed over geographic regions with different pollution profiles (Gauderman et al., 2000). However, steps such as identifying, contacting, recruiting, and monitoring a children population are difficult, especially in economically disadvantaged areas. A school-based strategy (Sexton et al., 2000) is relevant to select the study population to assess air exposures of schoolchildren and related health effects, but it is also important to improve the understanding of other factors (e.g. cultural, economic, psychological, social) affecting the willingness of families/children to participate in such studies.

Although the majority of the reviewed studies were cross-sectional, thus involving measurements at one specific point in time, ME modelling approach to assess children's exposure to air pollution was also reported in longitudinal (panel and cohort) studies. As far as known, the ME modelling approach was not used to study children's exposure to other compounds than combustion-related, ozone and radon, like for example biological compounds (aeropathogens, moulds and allergens) which have been proven to have negative effects on children's health, namely associated with respiratory symptoms, allergies, asthma and immunological reactions (Spengler and Sexton, 1983; WHO, 2009). However, nothing seemed to indicate the impossibility of its applicability to study exposures to that kind of pollutants. Although outcomes from the studies reviewed were mainly focusing on the characterization of children's personal exposures, other outcomes, like health ones were also reported.

There are several methods to obtain reliable data on time-activity patterns to use in a study on children's exposure assessment through a ME modelling approach, such as the recent geopositioning (GPS), accelerometer and photodiary methods. However, the main three methods found in the reviewed studies were time-activity diaries, questionnaires and surveys. In fact, the standard research tool is still the structured, self-reported and longitudinal diary (Decastro et al., 2007). Obtaining these diary data usually represents considerable effort in an exposure assessment study, due to the development of the diary structure, checks on subjects' reporting compliance and clarification of subjects' diary entries. Nowadays, new versions are being developed and used also on children's exposure studies like electronic time-activity diaries (Wu et al., 2005a). Another example is a broad time-activity patterns database, such as that of the National Human Activity Pattern Survey (NHAPS) in the United States, which is a 2-year probability-based telephone survey of exposure-related human activities, that has a primary purpose to provide comprehensive and current exposure information over broad geographical and temporal scales, particularly to use in probabilistic population exposure models (Klepeis et al., 2001). Questionnaires are also important tools as they are low cost and can be used to identify and quantify contacts with potential sources which is especially important to identify indoor sources that do not reflect the same mixtures than outdoor sources (Monn, 2001). Questionnaires can also provide other important information, like children's health symptoms, household characteristics and presence of environmental tobacco smoke. It is easily understandable that in the case of infants, toddlers and children, questionnaires should be filled by parents/guardians or with their support. Although seldom used on children studies, diaries and questionnaires can also be done as telephone surveys to the parents, as in the cases of Chau et al. (2002) and Lee et al. (2004), because in those cases they were found less expensive than paper ones. Freeman and Saenz de Tejada (2002) also reported direct observation and videography as useful methods to obtain time-activity information about small children. Daily basis time-activity patterns recordings were usual, but longer and shorter periods were also found, although rare. The longer the periods considered, the more reliable the information is. Although several time-intervals were used, 15-min intervals were the most common to record time-activity patterns information. However, to obtain children's time-activity patterns data longer periods (30-min) were also used, due to their lower mobility along the day when comparing to adults.

Time-activity patterns information allows identifying the optimum number of microenvironments that should be monitored. This is a crucial step to assess children's exposure to air pollution using a ME modelling approach. The most common microenvironments considered are merely reduced to outdoor and indoor (home and school). Children spend most of their time indoors and consequently, according to Ashmore and Dimitroulopoulou (2009), their personal exposure is dominated by air pollution in three microenvironments: home, school and transport. However, other authors considered multiple microenvironments in each one of these. In fact, home microenvironment is one of the major important contributors to children's personal exposure to air pollution. Sometimes it is possible to distinguish different patterns in the house characteristics in specific areas (e.g., inner-city, suburban), and relate it to predisposition to cause a particular health effect (Simons et al., 2007). A study in Bangladesh, from the World Bank (Dasgupta et al., 2006), suggested that young children's exposures vary considerably with households' conditions, which depends on the incoming and education of the families. For instance, indoor O_3 concentrations were associated with influences from the outdoor air and several housing characteristics (i.e., central air conditioning, fan use, and window opening) (Lee et al., 2004). Due to differences in exposures inside homes, particular microenvironments were usually considered to refine the study, as the example of kitchen, bedrooms, living rooms, garage, and home outdoor. Zipprich et al. (2002) found that close to 70% of the variation in adults and children's personal exposure to NO_2 and NO_x was due to exposure in the bedroom and other indoor locations, especially the kitchen. Also bedroom concentrations were found to explain 90% of the variation of the personal exposure to formaldehyde (Gustafson et al., 2005). Although not necessarily considered as microenvironments, there are some aspects related to home that significantly influence children's exposure to air pollution in this microenvironment, and should be taken into account, otherwise results could be deceivers. Tobacco smoking, gas-stove usage, outdoor temperature and wind speed, as well as the presence of wooden material, heating, and location in a suburb area, are determinants of indoor air quality in homes, and consequently influence exposures (Lai et al., 2006). Exposure in nurseries and schools, including children day care centres, has been somehow ignored, despite the fact that is a major contributor for children exposure to indoor air pollutants (Ashmore and Dimitroulopoulou, 2009), because children usually spend large amounts of time in there. A study from the United States Environmental Protection Agency (Ligman et al., 1999) concluded that particulate matter concentrations were higher in schools than in office buildings, as it was also higher indoors than outdoors (Stranger et al., 2008), although outdoor influence cannot be neglected. Inside the school, sometimes it is important to consider distinct microenvironments (e.g., kitchen, playground, different classrooms, and teacher's lounge), as stated by Mejía et al. (2011) in a recent review, in which the methodologies employed to assess the exposure of children to air pollutants at school were explored, namely how these methodologies influenced the assessment of the impact of this exposure on children's health, in particular related with traffic emissions. Outdoor environment is usually considered as a whole microenvironment. However, several differences were reported when assessing children's exposure to outdoor air in the school than in transit, for example. Thus, some studies divided the outdoor environment into several microenvironments, for example school outdoor, home outdoor and, the most common and important, in transit. Exposure in transit was also often ignored as an important contributor to children exposure to air pollution (Janssen et al., 2001). Although low when compared to the time spent in other microenvironments like home or school, children tend to spend some time commuting from home to school and vice-versa, by car, by bus, by bike or walking, and it is expected to have a significant influence to their exposure to air pollution, especially concerning combustion-related pollutants (Janssen et al., 2001; Van Roosbroeck et al., 2006). This was also stated by some studies that specifically showed influence of bus-commuting on children's exposure to air pollution, in particular to traffic-related air pollutants (Behrentz et al., 2005; Sabin et al., 2005).

After choosing the microenvironments for the study, it is necessary to obtain data from the pollutants' concentrations in those microenvironments. Data availability and its quality for model input are critically important. These data can be obtained by measurements in-situ (fixed or personal samplers) or by predictive models, and both cases were found in the reviewed studies. Predictive models included mass-balance or infiltration models, modelling from the fuel consumption and room characteristics. To estimate concentrations based on data from databases or previous studies in the literature was also found in the reviewed studies. ME monitoring is a special case of environmental monitoring in which the location where measurements are made is considered to be homogenous with respect to concentrations of the targeted pollutants over the averaging time of interest, and it should be consistent with the microenvironments considered to study. As a different example from the reviewed studies, Diapouli et al. (2007) developed experimental procedures to measure ultrafine particles' concentrations in different microenvironments (school, home and in-traffic), including: i) continuous monitoring outdoor and indoor schools (in different rooms) during school hours; ii) 24-hour indoor measurements in residences (in a bedroom, at breathing height); and iii) a counter placed on a co-driver's seat of a private car moving along selected routes. In the absence of data, indoor concentrations can be obtained by some existing predictive models as a function of ambient concentrations, effective penetration rates and contribution of indoor sources, as also exemplified by Chaloulakou and Mavroidis (2002) who predicted indoor air concentrations of CO at a public school, or by Kruize et al. (2003) in a Dutch population study (including children as a subpopulation group). Sensitivity analyses can be performed to determine the most significant factors of exposure. Furthermore, if the measurements are not conducted in collaboration with concurrent health studies, it could result in a low participant rate. The duration and time resolution of pollution measurements can vary from short to long periods and from single to multiple measurements' periods or campaigns. Multiple periods or campaigns seem to be useful to study seasonal variability of exposure (mainly in longitudinal studies). In fact, some authors found that personal exposure was significantly different by season, like Lee et al. (2013) found for NO_2.

Considering the ME modelling classification proposed by Milner et al. (2011), measurement-based was the ME model type found in almost all of the 26 reviewed studies, with exception of Hänninen et al. (2009), Shimada and Matsuoka (2011), and Wu et al. (2005b) which were found to be mass-balance ME models. Thus, the ME modelling approach in exposure assessment studies has several advantages for it takes into account the varying levels of pollution to which an individual is exposed during the course of the day (Malhotra et al., 2000). The key advantage of these models is that they are relatively straightforward to apply and produce results which may be easily compared with exposure observations (Milner et al., 2011). However, there are problems with both the limited temporal and spatial resolutions of these techniques. Nerriere et al. (2005) identified some of the main sources of error when applying a ME approach to assess children's exposure: i) method of recall, because frequently the data collected is based on the ability of the respondents to recall; ii) ability of respondent, for example sometimes the study can be hindered by the low literacy level of the study subjects; iii) nature of study, in itself contributes to a source of error, because it is difficult for any respondent, irrespective of the intellectual ability or memory, to account for every half an hour or even an hour in the daily schedule; and iv) difference between ideal and real situations, because in real social situations it is not possible to manipulate all the variables.

As reviewed by Milner et al. (2011), there are uncertainties associated with the application of exposure models, mostly due to the lack of detailed time-activity information or due to the assumptions and simplifications that are usually necessary along the assessment process. Thus, according to the same review, it is crucial for studies with exposure models to have a validation process. Sometimes this can be performed comparing ME concentrations of pollutants with direct personal exposure measurements in the entire or in a selected small group of the study population, so as to examine variations in results (Moschandreas and Saksena, 2002). In fact, only 5 of the 26 reviewed studies have not done any kind of validation process (Briggs et al., 2003; Saksena et al., 2003; Wang et al., 2008; Wu et al., 2005b).

Besides being a powerful tool to assess children exposure to air pollution, ME models can also have a potential opportunity to extrapolate data to an entire children population. Although not specific for children exposure assessment, there are examples of some models that were developed with the ability to predict personal exposure. Those models rely on the characterization of activity patterns of the population at risk as human activities impact the timing, location and level of personal pollutant's exposure, which is especially important for the evaluation of public policies and urban planning that may change the behaviour of individuals, resulting in a concurrent shift in the patterns of exposure experienced by the population (Schweizer et al., 2007).

5. Conclusions

From all the different available approaches and methods for determining exposure, the ME modelling approach (indirect approach) seemed to be the best to assess children's exposure to air pollution as it is faster and less expensive, and takes into consideration several levels of pollution to which a child is exposed during the course of the day. By considering the pollutants' concentrations in different locations attended by the study participants (microenvironments), and the time they spend in those locations (time-activity patterns information), it is possible to determine the children's exposure to air pollution, both in individuals and/or extend it to populations' groups.

There are a limited number of children's exposure assessment studies using the ME modelling approach. Since 2002, it was only possible to find and review 26 studies. Almost half of them were performed in the USA, but there were studies also performed in Europe, Australia, Latin America, India and Asia, which confirms the possibility of a worldwide application of the ME modelling approach to assess children's exposure to air pollution. Although the majority of the reviewed studies were cross-sectional, thus involving measurements at one specific point in time, ME modelling approach to assess children's exposure to air pollution was also found in longitudinal (panel and cohort) studies, which enhances the applicability of this approach to that kind of studies.

Those studies usually aimed to determine or characterize children's exposure to air pollution, but other outcomes were also reported. The methodology looks similar when using this approach on children or on adults' studies, however children's singularities lead to considerable differences in the application of this approach, like those related to the data collection: i) the methods for collecting time-activities patterns must be different; and ii) the time-activity patterns are itself different, which leads to choose different microenvironments to pollutants' concentrations data collection. In fact, to gather information on time-activity patterns, the most used methods were questionnaires and diaries, although different methods were also found to be feasible for children studies. Time-activity information led to the choice of the study microenvironments. The main microenvironments used were home and school (indoors and outdoors) and in traffic. Some of the studies reviewed divided home and/or school in different sub-microenvironments as kitchen, bedroom and different classrooms, but others can be considered. Data on pollutants' concentrations can be obtained by in-situ measurements (fixed or personal samplers) or by predictive models, respectively measurement-based and mass-balance models, and both cases were found in the reviewed studies. Some studies also reported this type of data estimated from databases or in the literature.

The use of the ME modelling approach in studies to assess children's exposure to air pollution is highly encouraged, as it has several advantages for it takes into account the varying levels of pollution to which an individual is exposed during the course of the day, being relatively straight forward to apply and produce results which may be easily compared with exposure observations. However, there are uncertainties associated with the application of this approach, mostly due to the lack of detailed time-activity information (particularly difficult in children studies), or due to the assumptions and simplifications that are usually necessary along the assessment process (existing in children's studies). Thus, a validation process is needed, which can be performed by comparing ME concentrations of pollutants with direct personal exposure measurements in the entire or in a selected small group of the study population.

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References

Adgate, J. L., Church, T. R., Ryan, A. D., Ramachandran, G., Fredrickson, A. L., Stock, T. H., et al., 2004a. Outdoor, indoor, and personal exposure to VOCs in children. Environ Health Perspect. 112**,** 1386-92.

Adgate, J. L., Eberly, L. E., Stroebel, C., Pellizzari, E. D., Sexton, K., 2004b. Personal, indoor, and outdoor VOC exposures in a probability sample of children. J Expo Anal Environ Epidemiol. 14 Suppl 1**,** S4-S13.

Akland, G.G., Hartwell, T.D., Johnson, T.R., Whitmore, R.W., 1985. Measuring human exposure to carbon monoxide in Washington, DC, and Denver, Colorado, during the winter of 1982-1983. Environ Sci Technol 19, 911-918.

Ashmore, M. R., Dimitroulopoulou, C., 2009. Personal exposure of children to air pollution. Atmospheric Environment. 43**,** 128-141.

Ballesta, P. P., Field, R. A., Connolly, R., Cao, N., Baeza Caracena, A., De Saeger, E., 2006. Population exposure to benzene: One day cross-sections in six European cities. Atmospheric Environment. 40**,** 3355-3366.

Baxter, L. K., Dionisio, K. L., Burke, J., Ebelt Sarnat, S., Sarnat, J. A., Hodas, N., et al., 2013. Exposure prediction approaches used in air pollution epidemiology studies: Key findings and future recommendations. J Expos Sci Environ Epidemiol. 23**,** 654-659.

Beamish, L. A., Osornio-Vargas, A. R., Wine, E., 2011. Air pollution: An environmental factor contributing to intestinal disease. Journal of Crohn's and Colitis. 5**,** 279-286.

Behrentz, E., Sabin, L. D., Winer, A. M., Fitz, D. R., Pankratz, D. V., Colome, S. D., et al., 2005. Relative importance of school bus-related microenvironments to children's pollutant exposure. J Air Waste Manag Assoc. 55**,** 1418-30.

Briggs, D. J., Denman, A. R., Gulliver, J., Marley, R. F., Kennedy, C. A., Philips, P. S., et al., 2003. Time activity modelling of domestic exposures to radon. Journal of Environmental Management. 67**,** 107-120.

Brook, R. D., Franklin, B., Cascio, W., Hong, Y., Howard, G., Lipsett, M., et al., 2004. Air pollution and cardiovascular disease: a statement for healthcare professionals from the Expert Panel on Population and Prevention Science of the American Heart Association. Circulation. 109, 2655-71.

Chaix, B., Gustafsson, S., Jerrett, M., Kristersson, H., Lithman, T., Boalt, A., et al., 2006. Children's exposure to nitrogen dioxide in Sweden: investigating environmental injustice in an egalitarian country. J Epidemiol Community Health. 60, 234-41.

Chaloulakou, A., Mavroidis, I., 2002. Comparison of indoor and outdoor concentrations of CO at a public school. Evaluation of an indoor air quality model. Atmospheric Environment. 36, 1769-1781.

Chau, C. K., Tu, E. Y., Chan, D. W. T., Burnett, J., 2002. Estimating the total exposure to air pollutants for different population age groups in Hong Kong. Environment International. 27, 617-630.

Crist, K. C., Liu, B., Kim, M., Deshpande, S. R., John, K., 2008. Characterization of fine particulate matter in Ohio: Indoor, outdoor, and personal exposures. Environmental Research. 106, 62-71.

Dasgupta, S., Huq, M., Khaliquzzaman, M., Pandey, K., Wheeler, D., 2006. Who suffers from indoor air pollution? Evidence from Bangladesh. Health Policy Plan. 21, 444-58.

Decastro, B. R., Sax, S. N., Chillrud, S. N., Kinney, P. L., Spengler, J. D., 2007. Modeling time-location patterns of inner-city high school students in New York and Los Angeles using a longitudinal approach with generalized estimating equations. J Expo Sci Environ Epidemiol. 17, 233-47.

Diapouli, E., Chaloulakou, A., Spyrellis, N., 2007. Levels of ultrafine particles in different microenvironments — Implications to children exposure. Science of The Total Environment. 388, 128-136.

Dons, E., Int Panis, L., Van Poppel, M., Theunis, J., Willems, H., Torfs, R., et al., 2011. Impact of time–activity patterns on personal exposure to black carbon. Atmospheric Environment. 45, 3594-3602.

Duan, N., Micro-environment types: A model for human exposure to air pollution. Department of Statistics, Stanford University, Stanford, California, 1981.

Duan, N., Models for Human Exposure to Air Pollution. U.S. Department of Health and Human Services, 1982.

Duan, N., Sauls, H., Holland, D., Micro-environment versus Personal Monitoring: Estimation of Exposure to Carbon Monoxide. In: R. G. Tardiff, B. Goldstein, Eds.), Methods for Assessing Exposure of Human and Non-Human Biota. John Wiley & Sons Ltd, 1991.

Edwards, R. D., Schweizer, C., Llacqua, V., Lai, H. K., Jantunen, M., Bayer-Oglesby, L., et al., 2006. Time–activity relationships to VOC personal exposure factors. Atmospheric Environment. 40**,** 5685-5700.

Freeman, N. C. G., Saenz de Tejada, S., 2002. Methods for collecting time/activity pattern information related to exposure to combustion products. Chemosphere. 49**,** 979-992.

Fugas, M., Assessment of total exposure to an air pollutant. Procedings of the International Conference on Environmental Sensing and Assessment, Paper No. 38-5, Vol. 2. IEEE #75-CH 1004-1 ICESA, Las Vegas, Nevada, 1975.

Gauderman, W. J., McConnell, R., Gilliland, F., London, S., Thomas, D., Avol, E., et al., 2000. Association between air pollution and lung function growth in southern California children. Am J Respir Crit Care Med. 162**,** 1383-90.

Gilliland, F., Avol, E., Kinney, P., Jerrett, M., Dvonch, T., Lurmann, F., et al., 2005. Air pollution exposure assessment for epidemiologic studies of pregnant women and children: lessons learned from the Centers for Children's Environmental Health and Disease Prevention Research. Environ Health Perspect. 113**,** 1447-54.

Gustafson, P., Barregard, L., Lindahl, R., Sallsten, G., 2005. Formaldehyde levels in Sweden: personal exposure, indoor, and outdoor concentrations. J Expo Anal Environ Epidemiol. 15**,** 252-60.

Hänninen, O., Kruize, H., Lebret, E., Jantunen, M., 2003. EXPOLIS simulation model: PM2.5 application and comparison with measurements in Helsinki. J Expo Anal Environ Epidemiol. 13**,** 74-85.

Hänninen, O., Zauli-Sajani, S., Maria, R., Lauriola, P., Jantunen, M., 2009. Integrated Ambient and Microenvironment Model for Estimation of PM10 Exposures of Children in Annual and Episode Settings. Environmental Modeling & Assessment. 14, 419-429.

Harrison, P. T. C., 1997. Health impacts of indoor air pollution. . Chemistry and Industry. 17, 677-681.

Harrison, R. M., Thornton, C. A., Lawrence, R. G., Mark, D., Kinnersley, R. P., Ayres, J. G., 2002. Personal exposure monitoring of particulate matter, nitrogen dioxide, and carbon monoxide, including susceptible groups. Occup Environ Med. 59, 671-9.

Hubal, E. A. C., Sheldon, L. S., Burke, J. M., McCurdy, T. R., Berry, M. R., Rigas, M. L., et al., 2000. Children's exposure assessment: a review of factors influencing Children's exposure, and the data available to characterize and assess that exposure. Environ Health Perspect. 108, 475-86.

Hulin, M., Caillaud, D., Annesi-Maesano, I., 2010. Indoor air pollution and childhood asthma: variations between urban and rural areas. Indoor Air. 20, 502-14.

Janssen, N. A. H., van Vliet, P. H. N., Aarts, F., Harssema, H., Brunekreef, B., 2001. Assessment of exposure to traffic related air pollution of children attending schools near motorways. Atmospheric Environment. 35, 3875-3884.

Jones, A. P., 1999. Indoor air quality and health. Atmospheric Environment. 33, 4535-4564.

Jones, J., Stick, S., Dingle, P., Franklin, P., 2007. Spatial variability of particulates in homes: Implications for infant exposure. Science of The Total Environment. 376, 317-323.

Klepeis, N. E., 1999. An introduction to the indirect exposure assessment approach: Modeling human exposure using microenvironmental measurements and the recent national human activity pattern survey. Environmental Health Perspectives. 107.

Klepeis, N. E., Modeling Human Exposure to Air Pollution. Exposure Analysis. CRC Press, 2006, pp. 445-470.

Klepeis, N. E., Nelson, W. C., Ott, W. R., Robinson, J. P., Tsang, A. M., Switzer, P., et al., 2001. The National Human Activity Pattern Survey (NHAPS): a resource for assessing exposure to environmental pollutants. J Expo Anal Environ Epidemiol. 11**,** 231-52.

Kollander, M., Statistical Methods to Estimate Human Exposure to Environmental Pollutants. In: R. G. Tardiff, B. Goldstein, Eds.), Methods for Assessing Exposure of Human and Non-Human Biota. John Wiley & Sons Ltd, 1991.

Kruize, H., Hanninen, O., Breugelmans, O., Lebret, E., Jantunen, M., 2003. Description and demonstration of the EXPOLIS simulation model: two examples of modeling population exposure to particulate matter. J Expo Anal Environ Epidemiol. 13**,** 87-99.

Lai, H. K., Bayer-Oglesby, L., Colvile, R., Götschi, T., Jantunen, M. J., Künzli, N., et al., 2006. Determinants of indoor air concentrations of PM2.5, black smoke and NO2 in six European cities (EXPOLIS study). Atmospheric Environment. 40**,** 1299-1313.

Lazenby, V., Hinwood, A., Callan, A., Franklin, P., 2012. Formaldehyde personal exposure measurements and time weighted exposure estimates in children. Chemosphere. 88**,** 966-73.

Lee, K., Parkhurst, W. J., Xue, J., Ozkaynak, A. H., Neuberg, D., Spengler, J. D., 2004. Outdoor/Indoor/Personal ozone exposures of children in Nashville, Tennessee. J Air Waste Manag Assoc. 54**,** 352-9.

Lee, K., Yeom, J., Yoon, C., Yang, W., Son, B.-S., Jeon, J. M., et al., 2013. Seasonal and geographic effects on predicting personal exposure to nitrogen dioxide by time-weighted microenvironmental model. Atmospheric Environment. 67**,** 143-148.

Ligman, B., Casey, M., Braganza, E., Coy, A., Redding, Y., Womble, S., 1999. Airborne Particulate Matter whithin school environments in the United States. Proceedins of Indoor Air. 255-261.

Lioy, P. J., 2010. Exposure science: a view of the past and milestones for the future. Environ Health Perspect. 118**,** 1081-90.

Liu, L. J., Box, M., Kalman, D., Kaufman, J., Koenig, J., Larson, T., et al., 2003. Exposure assessment of particulate matter for susceptible populations in Seattle. Environ Health Perspect. 111**,** 909-18.

MacIntosh, D. L., Spengler, J. D., Human Exposure Assessment. International Programme on Chemical Safety. World Health Organization, United Nations Environment Programme, International Labour Organization, 2000.

Malhotra, P., Saksena, S., Joshi, V., 2000. Time budgets of infants for exposure assessment: a methodological study. Journal Of Exposure Analysis And Environmental Epidemiology. 10**,** 267-284.

McGwin, G., Lienert, J., Kennedy, J. I., 2010. Formaldehyde exposure and asthma in children: a systematic review. Environ Health Perspect. 118**,** 313-7.

Mejía, J. F., Choy, S. L., Mengersen, K., Morawska, L., 2011. Methodology for assessing exposure and impacts of air pollutants in school children: Data collection, analysis and health effects – A literature review. Atmospheric Environment. 45**,** 813-823.

Mendell, M. J., 2007. Indoor residential chemical emissions as risk factors for respiratory and allergic effects in children: a review. Indoor air. 17**,** 259.

Mestl, H. E. S., Aunan, K., Seip, H. M., 2006. Potential health benefit of reducing household solid fuel use in Shanxi province, China. Science of The Total Environment. 372**,** 120-132.

Milner, J., Vardoulakis, S., Chalabi, Z., Wilkinson, P., 2011. Modelling inhalation exposure to combustion-related air pollutants in residential buildings: Application to health impact assessment. Environment International. 37**,** 268-279.

Mölter, A., Lindley, S., de Vocht, F., Agius, R., Kerry, G., Johnson, K., et al., 2012. Performance of a microenviromental model for estimating personal NO2 exposure in children. Atmospheric Environment. 51**,** 225-233.

Mölter, A., Lindley, S., de Vocht, F., Simpson, A., Agius, R., 2010a. Modelling air pollution for epidemiologic research – Part II: Predicting temporal variation through land use regression. Science of The Total Environment. 409**,** 211-217.

Mölter, A., Lindley, S., de Vocht, F., Simpson, A., Agius, R., 2010b. Modelling air pollution for epidemiologic research — Part I: A novel approach combining land use regression and air dispersion. Science of The Total Environment. 408**,** 5862-5869.

Monn, C., 2001. Exposure assessment of air pollutants: a review on spatial heterogeneity and indoor/outdoor/personal exposure to suspended particulate matter, nitrogen dioxide and ozone. Atmospheric Environment. 35**,** 1-32.

Moschandreas, D. J., Saksena, S., 2002. Modeling exposure to particulate matter. Chemosphere. 49**,** 1137-1150.

Moschandreas, D. J., Watson, J., D'Abreton, P., Scire, J., Zhu, T., Klein, W., et al., 2002. Chapter three: methodology of exposure modeling. Chemosphere. 49**,** 923-46.

Nerriere, É., Zmirou-Navier, D., Blanchard, O., Momas, I., Ladner, J., Le Moullec, Y., et al., 2005. Can we use fixed ambient air monitors to estimate population long-term exposure to air pollutants? The case of spatial variability in the Genotox ER study. Environmental Research. 97**,** 32-42.

Nieuwenhuijsen, M., Paustenbach, D., Duarte-Davidson, R., 2006. New developments in exposure assessment: The impact on the practice of health risk assessment and epidemiological studies. Environment International. 32**,** 996-1009.

Ott, W. R., 1982. Concepts of human exposure to air pollution. Environment International. 7**,** 179-196.

Peled, R., 2011. Air pollution exposure: Who is at high risk? Atmospheric Environment. 45**,** 1781-1785.

Rojas-Bracho, L., Suh, H. H., Oyola, P., Koutrakis, P., 2002. Measurements of children's exposures to particles and nitrogen dioxide in Santiago, Chile. Science of The Total Environment. 287**,** 249-264.

Rumchev, K. B., Spickett, J. T., Bulsara, M. K., Phillips, M. R., Stick, S. M., 2002. Domestic exposure to formaldehyde significantly increases the risk of asthma in young children. European Respiratory Journal. 20**,** 403-408.

Ryan, P. H., LeMasters, G. K., Levin, L., Burkle, J., Biswas, P., Hu, S., et al., 2008. A land-use regression model for estimating microenvironmental diesel exposure given multiple addresses from birth through childhood. Science of The Total Environment. 404**,** 139-147.

Sabin, L. D., Behrentz, E., Winer, A. M., Jeong, S., Fitz, D. R., Pankratz, D. V., et al., 2005. Characterizing the range of children's air pollutant exposure during school bus commutes. J Expo Anal Environ Epidemiol. 15**,** 377-87.

Saksena, S., Singh, P. B., Prasad, R. K., Prasad, R., Malhotra, P., Joshi, V., et al., 2003. Exposure of infants to outdoor and indoor air pollution in low-income urban areas - a case study of Delhi. J Expo Anal Environ Epidemiol. 13**,** 219-30.

Salvi, S., 2007. Health effects of ambient air pollution in children. Paediatric Respiratory Reviews. 8**,** 275-280.

Schwartz, J., 2004. Air pollution and children's health. Pediatrics. 113**,** 1037-1043.

Schweizer, C., Edwards, R. D., Bayer-Oglesby, L., Gauderman, W. J., Ilacqua, V., Jantunen, M. J., et al., 2007. Indoor time-microenvironment-activity patterns in seven regions of Europe. J Expo Sci Environ Epidemiol. 17**,** 170-81.

Sexton, K., Greaves, I. A., Church, T. R., Adgate, J. L., Ramachandran, G., Tweedie, R. L., et al., 2000. A school-based strategy to assess children's environmental exposures and related health effects in economically disadvantaged urban neighborhoods. J Expo Anal Environ Epidemiol. 10**,** 682-94.

Shimada, Y., Matsuoka, Y., 2011. Analysis of indoor PM2.5 exposure in Asian countries using time use survey. Science of The Total Environment. 409**,** 5243-5252.

Simons, E., Curtin-Brosnan, J., Buckley, T., Breysse, P., Eggleston, P. A., 2007. Indoor environmental differences between inner city and suburban homes of children with asthma. J Urban Health. 84**,** 577-90.

Sousa, S. I., Alvim-Ferraz, M. C., Martins, F. G., 2013. Health effects of ozone focusing on childhood asthma: what is now known - a review from an epidemiological point of view. Chemosphere. 90**,** 2051-8.

Sousa, S. I., Alvim-Ferraz, M. C., Martins, F. G., Pereira, M. C., 2009. Ozone exposure and its influence on the worsening of childhood asthma. Allergy. 64**,** 1046-55.

Sousa, S. I., Ferraz, C., Alvim-Ferraz, M. C., Vaz, L. G., Marques, A. J., Martins, F. G., 2012a. Indoor air pollution on nurseries and primary schools: impact on childhood asthma--study protocol. BMC Public Health. 12**,** 435.

Sousa, S. I., Pires, J. C., Martins, E. M., Fortes, J. D., Alvim-Ferraz, M. C., Martins, F. G., 2012b. Short-term effects of air pollution on respiratory morbidity at Rio de Janeiro--Part II: health assessment. Environ Int. 43, 1-5.

Spengler, J. D., Sexton, K., 1983. Indoor air pollution: a public health perspective. Science. 221, 9-17.

Steinle, S., Reis, S., Sabel, C. E., 2013. Quantifying human exposure to air pollution—Moving from static monitoring to spatio-temporally resolved personal exposure assessment. Science of The Total Environment. 443, 184-193.

Stranger, M., Potgieter-Vermaak, S. S., Van Grieken, R., 2008. Characterization of indoor air quality in primary schools in Antwerp, Belgium. Indoor Air. 18, 454-463.

Van Roosbroeck, S., Jacobs, J., Janssen, N. A. H., Oldenwening, M., Hoek, G., Brunekreef, B., 2007. Long-term personal exposure to PM2.5, soot and NOx in children attending schools located near busy roads, a validation study. Atmospheric Environment. 41, 3381-3394.

Van Roosbroeck, S., Wichmann, J., Janssen, N. A. H., Hoek, G., van Wijnen, J. H., Lebret, E., et al., 2006. Long-term personal exposure to traffic-related air pollution among school children, a validation study. Science of The Total Environment. 368, 565-573.

Wallace, L. A., Ott, W. R., 1982. Personal Monitors: A State-of the-Art Survey. Journal of the Air Pollution Control Association. 32, 601-610.

Wang, S., Zhao, Y., Chen, G., Wang, F., Aunan, K., Hao, J., 2008. Assessment of population exposure to particulate matter pollution in Chongqing, China. Environmental Pollution. 153, 247-256.

Weaver, V. M., Buckley, T. J., Groopman, J. D., 1998. Approaches to environmental exposure assessment in children. Environ Health Perspect. 106 Suppl 3, 827-32.

Weisel, C. P., 2002. Assessing Exposure to Air Toxics Relative to Asthma. Environmental Health Perspectives Supplements. 110, 527.

Wheeler, A. J., Wallace, L. A., Kearney, J., Van Ryswyk, K., You, H., Kulka, R., et al., 2011. Personal, Indoor, and Outdoor Concentrations of Fine and Ultrafine Particles Using

Continuous Monitors in Multiple Residences. Aerosol Science and Technology. 45, 1078-1089.

WHO, 2006. Air Quality Guidelines - Global Update 2005. World Health Organisation, Regional office in Europe, European Series, Copenhagen, Denmark.

WHO, 2009. WHO Guidelines for Indoor Air Quality - Dampness and Mold. World Health Organisation, Regional office in Europe, European Series, Copenhagen, Denmark.

Wu, C.-F., Delfino, R. J., Floro, J. N., Quintana, P. J. E., Samimi, B. S., Kleinman, M. T., et al., 2005a. Exposure assessment and modeling of particulate matter for asthmatic children using personal nephelometers. Atmospheric Environment. 39, 3457-3469.

Wu, J., Lurmann, F., Winer, A., Lu, R., Turco, R., Funk, T., 2005b. Development of an individual exposure model for application to the Southern California children's health study. Atmospheric Environment. 39, 259-273.

Ye, X., Fu, H., Guidotti, T., 2007. Environmental Exposure and Children's Health in China. Archives of Environmental & Occupational Health. 62, 61-73.

Yip, F. Y., Keeler, G. J., Dvonch, J. T., Robins, T. G., Parker, E. A., Israel, B. A., et al., 2004. Personal exposures to particulate matter among children with asthma in Detroit, Michigan. Atmospheric Environment. 38, 5227-5236.

Zhang, K., Batterman, S. A., 2009. Time allocation shifts and pollutant exposure due to traffic congestion: An analysis using the national human activity pattern survey. Science of The Total Environment. 407, 5493-5500.

Zhao, W., Hopke, P. K., Gelfand, E. W., Rabinovitch, N., 2007. Use of an expanded receptor model for personal exposure analysis in schoolchildren with asthma. Atmospheric Environment. 41, 4084-4096.

Zipprich, J. L., Harris, S. A., Fox, J. C., Borzelleca, J. F., 2002. An analysis of factors that influence personal exposure to nitrogen oxides in residents of Richmond, Virginia. J Expo Anal Environ Epidemiol. 12, 273-285.

Zou, B., Wilson, J. G., Zhan, F. B., Zeng, Y., 2009. Air pollution exposure assessment methods utilized in epidemiological studies. Journal of Environmental Monitoring. 11, 475-490.

Table 1 – Methods and approaches to assess children's exposure to air pollution: main advantages and limitations, and examples of children's studies.

Approach and method		Main advantages	Main limitations	Examples
Direct	Personal monitoring	- Simplicity of design - Freedom from modelling assumptions	- Expensive and time-consuming - Limited for large population studies (e.g. cohort/panel studies) and for young children	Gonzalez-Flesca et al. (2007); Thiriat et al. (2009); Buonanno et al. (2013); Both et al. (2013)
	Biomonitoring	- Useful measure of direct exposure - Aggregate over all sources and pathways	- Expensive and time-consuming - Complex methodologies - Hard to collect all of the info required to accurately estimate exposure	Delfino et al. (2006); Neri et al. (2006a); Neri et al. (2006b); Ruchirawat et al. (2007)
Indirect	Statistical regression models	- Frequently used in epidemiologic studies	- Limited to extrapolate to other locations and to other periods of time	Gauvin et al. (2002); Chaloulakou and Mavroidis (2002); Delfino et al. (2004); Zhou and Zhao (2012)
	CFD[a]	- Enables modelling at an extremely fine scale - Good as a research tool for ventilation, air flow and contaminants modelling	- Not considered appropriate for generic population exposure modelling - High technical and very specific knowledge and software are required	Huang et al. (2004); Valente et al. (2012)
	ME[b] modelling	- Conceptually easy to apply - Can be used to determine exposure to both individuals and large populations - Rapidly and inexpensively calculates exposures over various scenarios - The best way to predict the potential outcomes of future interventions and policies to reduce exposure	- There is a research need for its systematic validation	Mölter et al. (2012); Wang et al. (2008); Ballesta et al. (2006); Briggs et al. (2003)

[a]CFD – Computer Fluid Dynamics; [b]ME - Microenvironmental

Table 2 – Summary of the study design characteristics and outcomes of the reviewed studies using ME modelling approach to assess children's exposure to air pollution since 2002.

Reference	Study design						Outcomes
	Location	Study population	Calendar time	Pollutants analysed	Purpose	Type of study	
Lazenby et al. (2012)	2 suburbs of Perth, Western Australia	41 children aged 9-12 years	November 2006 to August 2007	Formaldehyde	To investigate seasonal variations in exposure.	Cross-sectional	Only a little variation detected between the seasonal monitoring periods, slightly higher in winter samples.
Mölter et al., (2012)	Secondary school in Greater Manchester, England	Children aged 12-13 years	30th April 2008 until 23rd January 2009	NO_2	To develop a new ME exposure model.	Cross-sectional	A ME model provides better exposure estimates than the nearest urban monitor or an outdoor pollution model.
Shimada and Matsouka (2011)	16 Asian countries	Population divided into sub-groups by age, of which children (0, 1-4 and 5-14) were considered	NR[a]	$PM_{2.5}$	To estimate exposure concentrations emitted through the consumption of fuel inside residences in individual countries in Asia, in order to assess associated health risks.	Cross-sectional	Individual exposure was greatly affected by people's use of time indoors. In each studied country, $PM_{2.5}$ exposure was higher for children and unemployed women aged 35-64.
Wheeler et al. (2011)	Windsor, Ontario, Canada	48 adults + 47 asthmatic children	2005 to 2006	Ultrafine particles (UFP), black carbon (BC) and $PM_{2.5}$	To examine the relationships between indoor and outdoor concentrations and personal exposures.	Cross-sectional	Mean outdoor concentrations were significantly higher than either indoor or personal ones. This exposure modelling estimation method performs well during different seasons when activity patterns and aerosols can vary.
Hänninen et al. (2009)	Turin and Bologna, Italy	333 school children (6-10 years) from Bologna + 101,563 children (0-14 years) from Turin	1st June 2004 to 31st May 2005 in Bologna and 14th January 2003 in Turin	PM_{10}	To present a ME and time-activity-based approach for exposure model to provide quantitative health-based tools for air quality-related policy refinement and evaluation.	Cross-sectional	Majority of the children were exposed to levels of health concerns in the case of an episode. Especially highest exposures experienced while in traffic may affect children spending substantial periods of time in or close to traffic environments.
Zhang and Batterman (2009)	USA	8297 people, of which 5.8% were 0-4 years old and 14.5% were 5-17 years old	NR[a]	Benzene and $PM_{2.5}$	To investigate changes in time allocation patterns and pollutant exposures that result from traffic congestion.	Cross-sectional	Changes in exposures depended on the duration of the congestion and the pollutant. Time allocation shifts and the dynamic approach to time-activity patterns improve estimates of exposure impacts from congestion and other recurring events.

Crist et al. (2008)	Columbus and Athens in Ohio, USA	30 Children, students from 4th and 5th grade elementary school	January 1999 to August 2000	$PM_{2.5}$	To characterize indoor, outdoor and personal PM exposures of school children.	Cross-sectional	At all the studied sites, personal $PM_{2.5}$ exposures were significantly affected by indoor $PM_{2.5}$, presumably the result of re-suspension by human activity.
Ryan et al. (2008)	Ohio, USA	642 children (age 0-36 months)	2001 to 2005	Diesel Exhaust Particles (DEP)	To estimate exposure to DEP, and to determine if exposure to high values of DEP during childhood increases the risk for developing allergic diseases.	Longitudinal	Using birth addresses to estimate a child's exposure may result in exposure misclassification for some children who spend a significant amount of time at a location with high exposure to DEP.
Wang et al.(2008)	Chongqing, China	Children (0-14), adults (15-64) and elders (>65)	2004 to 2006	PM_{10}	To determine population exposure to particulate matter.	Cross-sectional	Home was the largest contributor to personal exposure, especially on the rural areas, due to solid fuels burning. Elder people had higher exposure, due to more time spent in indoor microenvironments.
Zhao et al. (2007)	Denver, Colorado, USA	56 asthmatic children aged 6-13 years enrolled in the Kunsberg School	Two winters (October 2002-March 2003 and October 2003-March 2004)	$PM_{2.5}$	To identify and apportion the $PM_{2,5}$ sources that were common resulting in exposure to asthmatic children, and consequently interferes with regular school attendance and progress.	Cross-sectional	Secondary nitrate and motor vehicle emissions were the largest external sources of particulate matter. Cooking was the largest internal source. Also a significant influence of indoor smoking and high traffic flow outside the school in indoor air quality.
Van Roosbroeck et al. (2007)	Utrecht, Netherlands	54 children attending four different schools	NR[a]	$PM_{2.5}$, soot, NO_x and NO_2	To validate exposure classification based on school location.	Cross-sectional	The school's proximity to a freeway can be used as a valid estimate of exposure in epidemiological studies on the effects of the traffic-related air pollutants, soot and NO_x in children.
Van Roosbroeck et al. (2006)	Amsterdam, Netherlands	14 children aged 9-12 years	March to June 2003	NO, NO_2 and soot	To assess personal exposure to air pollution in children living in homes on streets with different degree of traffic intensity.	Cross-sectional	Children living near busy roads were found to have a 35% higher personal exposure to "soot", but smaller contrasts for NO and NO_2.
Ballesta et al. (2006)	Six European cities: Brussels, Lisbon, Bucharest, Ljubljana, Madrid and Dublin.	150 people, 25 of them school children, in each studied city.	22 October 2002, 27 May, 3 December 2003 and 28 April 2004.	Benzene	To assess population exposure to air pollutants in Europe, using one day cross-sectional campaigns.	Cross-sectional	Evident linear relationship between ambient levels and human exposure, although this was higher. Highest indoor concentrations were measured in bars and inside motor vehicles, due to tobacco and traffic influence.
Staff Mestl et al. (2006)	Shanxi province, China	Population from rural area of Shanxi and urban area of Taiyuan, divided in age	NR[a]	PM_{10}	To estimate daily average exposure for different population groups: rural coal users, urban coal users, and urban gas users.	Cross-sectional	Young children and elderly spend most the time indoors and had the highest daily exposure in the coal using population. The rural population experienced higher exposure than the urban ones, even though the outdoor air is significantly cleaner in rural areas.

		groups (0-1; 2-6; 7-14: 15-64; >65)					
Wu et al. (2005a)	Alpine, California, USA	20 asthmatic children aged 9-17 years attending 5 different schools	September-October 1999, April-June 2000	$PM_{2.5}$	To characterize children's short-term personal exposures and separate them into ambient and non-ambient components. 2 different model approaches were used.	Longitudinal (panel study)	Study subjects only received 45% of their exposure indoors at home, even though they spent more than 60% of their time there. 29.2% of their exposure was received at school, where they spent only 16.4% of their time.
Wu et al. (2005b)	Southern California, USA	5000 children aged 9-18 years from Southern California Children's Health Study (CHS)	NR[a]	CO, NO_2, PM_{10}, $PM_{2.5}$ and elemental carbon	To investigate the relationship between air pollution and children's chronic respiratory health outcomes.	Cross-sectional	Local traffic significantly increased within-community variability for exposures. Inter-community exposure differences were affected by location, traffic density, locations of residences and schools, and time activity patterns of the children.
Adgate et al. (2004a)	Minneapolis, Minnesota, USA	153 children (from 2nd to 5th grade) attending two different schools.	November 1999 to May 2000	VOC (15 compounds)	To characterize air pollution exposures in inner-city children predominantly from low-income households for providing benchmarks.	Cross-sectional	Media and upper-bound home and personal exposures were well above health benchmarks for several compounds, so outdoor measurements likely underestimate long-term health risks from children's exposure to these compounds.
Adgate et al. (2004b)	Minneapolis, Minnesota, USA	Probability sample of children (3-12 years) from 284 households.	May to September 1997	VOC (10 compounds)	To determine and compare personal, indoor and outdoor exposure, and statistical associations with common sources and modifiers of exposure.	Cross-sectional	A consistent pattern of personal > indoor > outdoor exposure was observed for 9 of 10 VOC. For most children, the indoor at-home microenvironment was strongly associated with personal exposure.
Lee et al. (2004)	Nashville, Tennessee, USA	36 elementary school children (10 to 12 years). 99 children provided additional time-activity info.	June and July 1994	O_3	To determine weekly outdoor, indoor and personal exposure estimates of school children. To determine if systematic exposure differences among children exist.	Cross-sectional	Personal O_3 exposures reflected the proportional amount of time spent in indoor and outdoor environments (higher out). Centrally air-conditioned indoor environments confer a substantial protect from ambient O_3 levels.
Yip et al. (2004)	Detroit, Michigan, USA	20 children, aged 7-11 years with asthma	2000 to 2001	PM_{10}	To characterize the children's personal exposures with respect to the measured values at the ambient sites, in the classrooms, and in the homes.	Cross-sectional	Children's personal exposure strongly correlated with their home environment and weak correlations with the ambient (outdoor) and classroom environments.
Briggs et al. (2003)	Northampton and Kingsthorpe, UK	567 adult residents + 247 college students +	1998 to 1999	Radon	To model potential exposures to radon in domestic environment for different population sub-groups	Cross-sectional	Students and schoolchildren were found to have the lowest home occupancy, consequently they were found to have the lowest home radon exposure.

		447 schoolchildren (9-13 years old)					
Liu et al. (2003)	Seattle, USA	89 elderly people + 19 children with asthma (6-13 years old)	1999 to 2001	$PM_{2.5}$ and PM_{10}	To examine the particulate matter exposures and health effects in individuals.	Longitudinal	When personal exposures were directly measured, asthmatic children had the highest exposures. However, this model based on the three MEs did not well correlated with the measured values for PM personal exposure of asthmatic children.
Saksena et al. (2003)	Delhi, India	Infants and women from two slums	December 1994 to February 1995	Respirable Suspended Particles (RSP) and carbon monoxide	To assess the daily exposure of infants (and their mothers) and to determine the factors that influence exposure.	Cross-sectional	Indoor background levels during the day and at night-time exceedingly high, due to re-suspension of dust and infiltration. Outdoor levels measured poorly correlate with integrated exposure.
Chau et al. (2002)	Hong Kong	396 Hong Kong inhabitants, of which 14 were children (<14 years old)	April to August 1998	CO_2, CO, NO_2 and PM_{10}	To estimate the total exposure to air pollutants for different population age groups, and to compare their exposure profiles with respect to different commuting and behaviour patterns.	Cross-sectional	Homes were shown to be one of the major exposure sites for all age groups. 24h NO_2 exposures for individuals spending more than 2h in commuting daily exceeded the 24h NO_2 exposure standards.
Harrison et al. (2002)	Birmingham, UK	11 healthy adult subjects and 18 members of groups more susceptible to adverse health changes (including 6 schoolchildren ~10 years old)	NR.[a]	PM_{10}, NO_2 and CO	To investigate the relation between personal exposure and exposures estimated from static concentrations measured within the same microenvironments, for healthy individuals and susceptible groups.	Cross-sectional	ME measurements of CO and NO_2 can well represent the personal exposures of individuals within that ME. Elderly subjects and those with pre-existing disease received generally lower PM_{10} exposures than the healthy adults and schoolchildren, due to their less active lifestyles.
Rojas-Bracho et al. (2002)	Santiago, Chile	20 children (age 10-12 years), living in non smoking households	NR.[a]	$PM_{2.5}$, PM_{10} and NO_2	To characterize particle and gaseous exposures of children (aged 10-12 years), living in Santiago, Chile	Cross-sectional	Outdoor particles contributed significantly to indoor concentrations. The presence of gas cooking stoves in the homes results in NO_2 weak associations for indoor-outdoor and personal-outdoor relationships.

a) N.R. - Not reported

Table 3 – Summary of data collection characteristics of the reviewed studies using ME modelling approach to assess children's exposure to air pollution since 2002.

Reference	Time-activity patterns			Pollution measurements		
	Methods of collection	**Record time**	**Key elements included**	**Microenvironments**	**Methods of collection**	**Duration and time resolution**
Lazenby et al. (2012)	Daily activity diary and a questionnaire.	15-min intervals of each 24-h record period.	Information about the indoor and outdoor environment, children's lifestyle and activities.	Indoor domestic, outdoor domestic, school indoors	Microenvironment concentrations were passively collected using a badge sampler. Also personal badge samples were made to compare the results.	24-h periods: one weekday and one weekend.
Mölter et al. (2012)	Time activity diary, filled in by the participants.	15-min time intervals.	ME, period of time, additional information on home characteristics.	Home, school and journey (all indoor and outdoor). Home indoor divided into kitchen, living room, and child's bedroom.	Home indoor calculated through an indoor exposure model. School indoor also estimated. Outdoors from the nearest urban monitoring system. Also use of a personal sampler.	2 days in each one of the four seasons (Spring, Summer, Autumn and Winter), for both stationary and personal.
Shimada and Matsouka (2011)	Several time-use surveys data in Asia region.	NR[b]	The daily life children activities were adapted from the adult surveys.	Home indoors: kitchen and living room; heating; illumination.	Estimated from the fuel consumption and room characteristics.	NR[b]
Wheeler et al. (2011)	Time activity diary (TAD).	15-min and 30-min, intervals for adults and children respectively.	Information on activities and presence in various locations and on whether the participants were close proximity to smokers, and for how long.	According to TAD: indoors (at home, away and at school), and outdoors (at home, away and in vehicles).	Integrated and continuous monitors were employed to measure indoor and outdoor particles and BC (only at home). Personal sampling was also conducted.	5 sampling days each in the winter (January-March) and summer (July-August) of each year for stationary, and only in 2006 for personal.
Hänninen et al. (2009)	Information derived from school administration, from a survey on two children samples, and using typical daily timetables of schoolchildren in Italy.	NR[b]	Estimation on time spent travelling between home and school.	Residential indoors, school indoors, in traffic and residential outdoors	Indoor concentrations were modelled using either a mass-balance model or infiltration model. Outdoor and in-traffic concentrations were estimated using fixed site monitoring stations (the last one multiplied by coefficients observed in a number of studies reviewed by WHO).	1 school year in Bologna and 1 day in Turin
Zhang and Batterman (2009)	From the National Human Activity Pattern Survey (NAHPS),	Variable, depending on the answers.	Locations and activities in a diary for a 24-h period, along with	Indoor: Home, workplace, shopping, bar/restaurant, school/public building,	Concentrations were based on recent literature, and Monte Carlo analyses were used to address both the variation and uncertainty in the available data.	NR[b]

	developed by the USEPA.		basic socio-demographic data.	other; outdoor: near road and other; transport: in-vehicle		
Crist et al. (2008)	NR[b]	NR[b]	NR[b]	School indoors (selected classroom away from the kitchen) and school outdoors	Indoor monitors during the classroom's usage time. Continuous ambient monitor to measure outdoor concentrations. Also personal samplers (pumped) – one student per classroom.	Daily (24-h) both for indoor and ambient. Also school day period (8 a.m. to 3 p.m.) for ambient, indoor and personal.
Ryan et al. (2008)	Annual complete parental report of the locations where child spent eight or more hours per week, in the last 12 months.	1 complete year (12 months)	Locations where children spent eight or more hours per week. Additional health information in the questionnaire.	Home and non-home environments (includes daycare, babysitter, relative's home or other locations)	A land-use regression (LUR) model was developed using geographic data as independent variables and sampled levels of a marker of DEP as the dependent variable.	Daily levels obtained of each sampling site, averaged to minimize the effect of seasonal and temporal variations as health outcomes were measured annually.
Wang et al.(2008)	Recall questionnaire sent to families.	A full 7-day period report, between January and March 2006	Time spent in the different MEs considered.	Kitchen, bedroom, living room, school/work, other indoors away from home, transit, and outdoors	Outdoor concentrations from air quality monitoring stations. Indoor concentrations measured at 21 sites containing major indoor MEs. In transit levels were estimated based on data from literature.	Indoor measurements conducted continuously for at least 24 h. Outdoor data for each month of 2004 available at 10 ambient air quality monitoring stations.
Zhao et al. (2007)	NR[b]	NR[b]	NR[b]	Indoor (inside school) and outdoor (outside school)	Fixed monitors were located in the main corridor of the school (indoor) and outdoors on the roof of the school. Use of personal samplers (pumped) to personal monitoring (for comparison).	Continuous measurements (24 h), both for indoor, outdoor and personal.
Van Roosbroeck et al. (2007)	Questionnaire on time-activity patterns.	N.R.[b]	Daily activity patterns, school travel mode and additional data on housing conditions and possible indoor sources.	Outdoor and indoor at school (and personal for comparison)	Personal monitoring was performed in 48-h periods, by a personal wearable bag sampler. Indoor and outdoor measurements were done using the same equipment as for personal sampling, but with a shelter.	48-h measurements periods, from Monday to Wednesday and from Wednesday to Friday.
Van Roosbroeck et al. (2006)	Questionnaire on time-activity patterns.	N.R.[b]	Additional information on possible indoor sources.	Outdoor and indoor (school and home).	Personal monitoring was performed by a personal wearable bag sampler. Outdoor measurements were done using the same equipment.	Measurements took place from Monday to Wednesday or from Wednesday to Friday, in a total of 8 measurement periods of 48 h.

Ballesta et al. (2006)	Time-micro-environment-activity diary.	Data entered into a database file that recorded intervals of 15-min	Movements and activities of the sampled population.	Outdoor: city background and hot spots. Indoor: homes and specific locations (schools, offices, shops and bars)	Simultaneous diffusive measurements of outdoor, indoor and human exposure benzene concentrations.	Measurements were made during one day campaigns, on six groups.
Staff Mestl et al. (2006)	Based on earlier publications: urban from a Hong Kong study and rural from a Bangladesh study.	Depending on the earlier publications	Information about the variability of the number of hours spent in the different MEs.	Indoor: kitchen, bedroom, living areas, school/work; and outdoors	Indoor concentrations were estimated based on data from previous studies. Outdoor concentration levels were estimated by an air dispersion model (AERMOD).	Depending on the previous studies.
Wu et al. (2005a)	Electronic time-activity diary used by the subjects.	24-h recordings, with 15-min resolution	Time, locations and activities.	Indoor (home, school and other places), and outdoor (home, other places, and on road or in transit).	To measure outdoor concentrations central-site fixed stations were used. Personal nepholemeters to measure indoor concentrations and personal exposure to compare with the modelling results.	Two 14-day runs in 1999 and five runs in 2000, where 1-min PM concentrations were determined continuously.
Wu et al. (2005b)	Using information from a time-activity survey administered twice a year to each child, and from the Consolidated Human Activity Database developed by the USEPA.	24-h time-activity series (15-min intervals) for each child	How much time (by 5 categories) they spent outdoors, and also if they spent more than 15 min daily travelling between school and home and by what means.	Residential (indoor and outdoor), school (indoor and outdoor), and in vehicle.	Combine of central-site ambient observations with 2 dispersion models to estimate outdoor concentrations: CALINE4, to traffic emissions; and SMOG airshed model, to transported pollutants and non-mobile sources. A single-compartment steady-state mass balance equation to estimate indoor concentrations.	N.R [b]
Adgate et al. (2004a)	Each subject kept a time-activity diary.	24-h recordings	Time spent in 7 primary MEs as well as data on exposure to tobacco smoke and other potential modifiers.	Indoors: child's home, five randomly selected classrooms in each school; outdoor at each school.	Personal and home measurements were collected continuously for 2 days; school measurements after school hours; and outdoor measurements continuously from Monday to Friday	Winter (24 Janurary – 18 February) and Spring (9 April – 12 May) 2000
Adgate et al. (2004b)	Each subject kept a time-activity diary.	24-h recordings	Time spent in 7 primary MEs as well as data on exposure to tobacco smoke and other potential modifiers.	Indoor (at home, school and other); outdoor (home, school and other); and in transit.	VOCs were collected by passive diffusion, indoor and outdoor urban and nonurban residences. Also personal sampling was carried to compare the results.	Screening-phase, followed by an intensive-phase. 6-day average concentrations on fixed monitors (indoor and outdoor) and in personal samplers.
Lee et al. (2004)	Activity diaries collected during	Daily activities from 8:00 a.m. to 9:00 p.m.	Times, location and activities.	School and home, both indoors and outdoors.	Continuous outdoor and passive indoor and outdoor home measurements were	6 week monitoring period during the school's

	sampling period. 99 children provided additional info on time-activity by telephone interview.	for a sample of 15 non-consecutive days			done. Each participating child and family had a set of personal (wearable) passive O_3 samplers to personal sampling (compare the results).	summer vacations, in June and July of 1994.
Yip et al. (2004)	Children recorded their activity in logs.	24-h recordings	Time, location and activities.	School and home, both indoors and outdoors.	Daily ambient and indoor measurements at two elementary schools, as well as concurrent measurements inside the children homes. Personal samplings also made.	Daily 24-h measurements were made in 8 seasonal sampling campaigns.
Briggs et al. (2003)	Survey of home occupancy rates, and surveys of time activity and journey patterns.	Over a 24-h weekday period, for half-hourly intervals.	Daily time spent indoors home, other time-activity and journey patterns.	Home outdoors, home downstairs, home upstairs.	Radon levels obtained for a representative occupied house, by continuous monitoring.	Continuous monitoring over an 18 day period.
Liu et al. (2003)	Individual diary.	Daily, with a 15-min time intervals.	Time, activity and location. Additionally, technicians recorded occurrence of events that potentially affect PM concentrations at homes.	Indoor (including home and other places), outdoor near home, and outdoor away from home.	Indoor and outdoor PM concentrations were measured with single-stage inertial monitors. Personal monitoring was also measured using a personal monitor device for comparison with the modelled values.	26 monitoring sessions, each one with 10 consecutive monitoring days, starting on Tuesdays and ending on Fridays.
Saksena et al. (2003)	Estimated through recall-based questionnaires.	NR[b]	Time spent in the six MEs.	The three cooking sessions, the session between meals which could be spent indoors or outdoors, and the sleeping session.	Concentration levels were measured using portable samplers, for two consecutive days in each house.	Continuously (24-h) for two consecutive days.
Chau et al. (2002)	Time diaries obtained from recall questionnaires by telephone.	7-day, with 15-min time intervals.	Both socioeconomic characteristics of the respondents, locations and activities on weekdays and weekends.	20 grouped in: Indoor at home, Indoor away from home, enclosed traffic and outdoor.	Directly measured in the major MEs, and obtained by the data reported in various open literature for the remaining MEs.	NR [b]
Harrison et al. (2002)	Activity diaries.	N.R.[b]	The periods of time spent by the subject in the different MEs.	Outdoor and indoor (home and workplace/school). Additional MEs: leisure activities (social clubs, pubs and cafes), transport (cars,	Static measurements were performed in the indoor and outdoor microenvironments. Additionally, direct personal measurements were performed in healthy subjects. In susceptible subjects, a shadowing approach was performed for the	Continuously. Duration not reported.

				buses and trains), shops and park area (dog walking).	additional direct personal sampling to compare the results.	
Rojas-Bracho et al. (2002)	Time-activity diary. A recall diary was also used to report activities and conditions that could affect indoor concentrations or personal exposures.	N.R.[b]	Time intervals spent in different MEs, time spent near smokers, and specific info on buildings.	Indoors, outdoors, and in transportation (motor vehicle, walking or bicycle).	Indoor and outdoor samples were done by passive badges. Personal samples were done by a pumped wearable device to compare the results.	Personal, indoor and outdoor 24-h samples were collected for five consecutive days.

a) according to Milner et al. (2011); b) NR – not reported