World Health Organization

Model documentation:
WHO Household Multiple Emission Sources (HOMES) Model

Table of Contents

1. Introduction

The WHO Household Multiple Emissions Sources (HOMES) model predicts indoor concentrations and personal exposures of air pollutants associated with combusting fuels for cooking, lighting, heating and other household energy needs. The HOMES model incorporates emission rates and usage times of indoor sources; a room's ventilation rate and volume; the fraction of emissions from the sources that enter the room (which can be important for chimney stoves); and the background/ambient concentration of pollution. The model estimates kitchen concentrations and personal exposures and associated relative risks by applying assumptions about:

1. the ratio of room concentrations to personal exposure of fine particulate matter ($PM_{2.5}$) or the amount of time an individual spends in the kitchen, and;
2. the integrated exposure-response functions used to estimate the relative risk of acute lower respiratory infection (ALRI) based on exposure to $PM_{2.5}$.

The model is primarily designed for application with $PM_{2.5}$ and carbon monoxide, as these two pollutants are both commonly emitted by indoor combustion sources and have well-established Air Quality Guidelines (WHO, 2006, 2010, 2014).

The model has been designed to represent the range of environmental and operational conditions expected for the population of interest, by using distributions of input parameters to produce a distribution of predicted indoor air pollution concentrations. This approach, in contrast to using single point estimates, better represents reality as air pollutant levels in homes also vary.

The model provides a method for users to evaluate the potential implications of various intervention scenarios for a given population or context. Users can input data on up to three different technologies (including traditional or "improved" cookstoves), and the model will output the expected kitchen concentration, personal exposure and level of ALRI relative risk. For example, users can explore what air quality level and exposure would result from a given combination of technology performance and usage, which can be helpful for program planning. The results can help inform which technologies are recommended for programmatic interventions and the degree to which traditional technologies need to be displaced. Should data on emissions performance, stove usage, and environmental conditions (ventilation and kitchen volumes) be available for an intervention or program, the impacts on kitchen concentrations and personal exposures can also be modelled using HOMES. Importantly, the model is only intended to illustrate potential air quality and exposure scenarios; it does not replace field assessments.

The HOMES model is forward-looking in estimating kitchen concentrations and exposures resulting from up to three emissions sources. To derive specific emissions performance which would result in meeting air quality targets, the complimentary WHO Performance Target (PT) model should be used. The PT model was developed to help guide the establishment of emissions performance targets, whereas the HOMES model is designed to explore how different combinations of performance from multiple sources may affect potential kitchen concentrations and personal exposures.

This document explains the theoretical underpinnings of the model and background for its development and serves as a guide to running the web-based model.

2. HOMES model theory and background

The relationship between emission sources and indoor air concentrations involves several factors, as shown in Figure 1, although stove emissions are generally the key driver of indoor air quality. As this model is primarily designed for use with cookstoves, this document will focus on this specific emissions source. However, the model may also be used to calculate estimated kitchen concentration and personal exposure from use of devices including heat stoves or lights, as long as the relevant input data is available for these devices. At any given air change rate (or the degree to which pollution escapes from the indoors) and room size, stoves that emit low quantities of pollutants into the indoor environment per day are likely to result in lower average household air pollution (HAP) concentrations than those that emit high amounts.

Actual emissions and HAP, however, may be influenced by use of several stoves over the day, as multiple stove use is commonly employed to meet the variety of cooking and heating needs in a home (Lewis and Pattanayak, 2012; Masera et al., 2000; Ruiz-Mercado et al., 2011). Furthermore, the frequency and duration of stove use changes over time due to factors such as seasonal demands for heating or cooking, fuel availability and cost, as well as the condition of the stove or other device. HAP is also impacted by infiltration of ambient air pollution, as well as local outdoor factors, such as re-infiltration of stove emissions (especially important for chimney stoves).

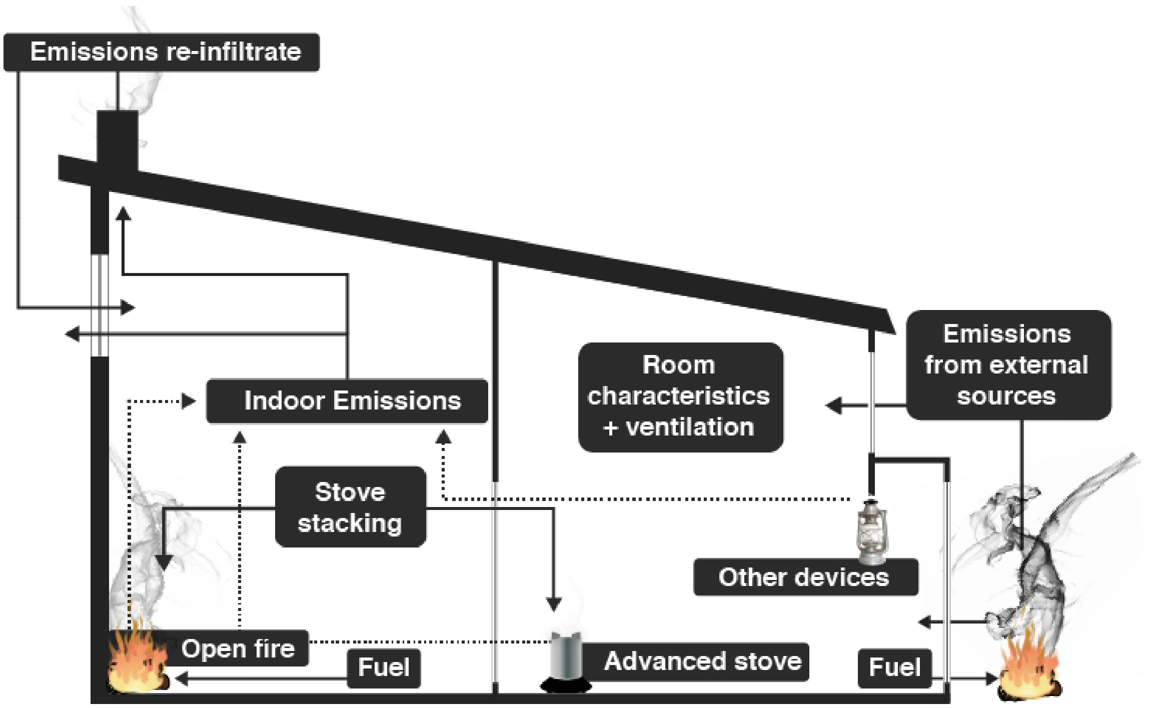

Figure 1. Factors impacting indoor air quality
Note: figure produced by Ajay Pillarisetti, UC-Berkeley

Modelling air pollutant concentrations with a single-zone model

A simple construct to relate indoor emissions sources with HAP concentrations is a single-zone model. In this context, the single zone is the room were the emissions sources are located, and it is assumed that any pollutant emitted into room air is uniformly mixed. The room receives fresh air at a given rate through natural infiltration and/or mechanical means, and this supply is matched by an outflow of room air by exfiltration and/or mechanical means at the same rate.

The effect of an **exhaust chimney, hood, or other venting mechanism** which removes emitted pollutants before they mix into the general kitchen air, can also be accounted for by applying fraction term to the emissions rate. Contributions from the emissions sources are defined by an emission rate. The duration of the emissions is also an important input parameter. Based on these parameters, the concentrations of a room can be estimated over time.

The model assumes that all emission sources are in **a single room**, which is labelled "**kitchen**"; however, the model can be run for any room as long as the appropriate input data is used. At this time, the model cannot be used to model multiple emission sources in different rooms.

The model also assumes that if multiple emission sources are used (up to three), these emissions occur simultaneously. Although this is not realistic of many real-world settings, this approach is taken for computational simplicity, and makes little difference to the 24-hr pollutant concentration results generated by HOMES (note: simultaneous use of devices leads to higher peak concentration levels than having them occur separately, but all concentration results presented by HOMES are averaged over 24 hours).

The single-zone model approach has been applied in the household energy sector in developing countries as early as the 1980s (Smith et al., 1983). Smith et al. (1983) used a single zone model to predict kitchen concentrations of particulate matter and benzo(a)pyrene resulting from cooking with solid fuels in India. A similar single zone modelling approach was employed by Prasad et al. (1985) to predict indoor CO concentrations resulting from cookstove emission (Prasad et al., 1985). Single-zone models have also been used in reverse to estimate emission factors for cookstoves (McCracken and Smith, 1998), and for kerosene lamps (Apple et al., 2010; Schare and Smith, 1995). More recently, single-zone models were used to help characterize the variability in HAP concentrations and the implications for study design (L'Orange et al., 2015), and to illustrate a framework for combining stove usage and performance to estimate the impacts of a given program or intervention (Johnson and Chiang, 2015a, 2015b). Single-zone models are also commonly employed in other contexts for air pollution and climate studies (Bond et al., 2011; Hellweg et al., 2009; Nicas, 2009), as well as tools for estimating indoor exposures and health risks such as the USEPA IAQX model (USEPA, 2000).

The single-zone model described here is based on the work by Johnson et al. 2011, which was originally developed and presented based on fieldwork in India (Johnson, 2011). A simplified version of that model then was used to develop emissions performance targets for the ISO International Workshop Agreement 11:2012: Guidelines for Evaluating Cookstove Performance (ISO, 2012). Later, the model was used to derive emission rates targets for the WHO Guidelines for Indoor Air Quality: Household Fuel Combustion (Johnson et al., 2014; WHO, 2014).

While the model is a relatively simple construct and some of the assumptions simplify the complexity of real-world conditions, its performance has been sufficient for providing constructive guidance. The estimated concentrations provided by the model, when compared to those measured in relevant contexts have been reasonably similar, as shown in the evidence chapter for the WHO Guidelines for Indoor Air Quality: Household Fuel Combustion (Johnson et al., 2014). Figure 2, below, from this evidence chapter on the model shows that the modelled distributions and measured distributions for various stove/fuel combinations overlap substantially.

Stove/fuel type	$PM_{2.5}$ (μg/m^3)		CO (mg/m^3)	
	Model	Observed	Model	Observed
Traditional solid fuel	>60% in range 500 – 1,800 Mode: 800	Mean: 826 (SD=1038) (SEAR); 972 (SD=876) (all regions)*	>60% in range 5 – 25 Mode: 12	Mean: 11.09 (SD=8.03) (SEAR); 9.94 (SD=7.11) (all regions)*
Unvented rocket-style stove	>60% in range 200 – 1,500 Mode: 500	Mean 410 (range 170 – 1,180)**	>60% in range 2 – 15 Mode: 5	Mean 7.56 (range 5.04 – 17.99)**
Gas	99% would meet IT-1 (35)	All clean fuel; mean: 72 (SD=41) (SEAR); 66 (SD=37) (all regions)*	All would meet the 24-hr AQG (7)	All clean fuel: mean: N/A (SEAR); 1.49 (SD=0.69) (all regions)*

*Data from systematic review of pollutants levels of HAP and exposure (see Review 4) **Data from systematic review of Intervention impacts (see Review 5)

Figure 2. Comparison of model predictions and observed concentrations of $PM_{2.5}$ and CO. (Reproduced from (Johnson et al., 2014)

It is also important to note that other modelling approaches, such as a multi-zone model which divides the room of interest into different sections, could also be used with a Monte Carlo approach, but have not yet been applied to relate indoor air quality with stoves and other household energy devices in the developing world. Computational fluid dynamic (CFD) models, while providing spatially detailed concentration estimates for a given room, are computationally intensive and require highly detailed characteristics of the room and emission source (Jarod Maggio, 2013). Although parametric CFD models can be constructed where model parameters are systematically varied, the requirements for detailed input data and extensive computation means CFD models are not well-suited for representing populations of households. The single-zone model, conversely, requires fewer assumptions compared to other modelling approaches, can be applied across a range of conditions to represent a broad spectrum of households, and has been applied specifically to household energy use in developing countries.

HOMES Model Description

This model builds on the previous work and approaches to estimate exposure and associated relative risks, including the option of modelling up to three sources. Mathematically, the model is described as:

Equation 1. $C(t) = \frac{q_1f_1+q_2f_2+q_3f_3+\ldots q_nf_n}{\alpha V}(1\text{-}e^{-\alpha t})+C_o(e^{-\alpha t})+C_b$,

where

$C(t)$ = Concentration for a given time point
q_x = emission rate for source x (mass/min)
f_x = fraction of emissions from source x that enters the kitchen environment
α = air change rate (changes/min)
V = kitchen volume (m^3)
t = time interval (1 min)
C_o = concentration from preceding time interval (unit mass/m^3)
C_b = Background concentration (assumed to be the outdoor ambient concentration [mass/m^3])
Note: To isolate only the impact from any given source, the background concentration can be set to 0, although this approach will not estimate true exposure.

The model produces 24 hours of minute-by-minute concentration estimates (1440 minutes), where the emission rates for the respective sources are input for three discreet, evenly spaced periods. The sum of these periods is the device usage time, which is also a model input. Evenly spaced periods are used for the model for computational simplicity, and in practice different spacing - which may reflect actual use more realistically - makes little difference to the 24-hr pollutant concentration results. Note that the model assumes the background concentration in the room (C_b) is equal to the outdoor ambient concentration.

To calculate the predicted 24hr-mean concentration in the kitchen (C_k), the concentrations for each time point (C_i) are summed over the day and divided by the number of minutes in a day.

Equation 2. $C_k = \sum_1^{1440} \frac{C_i}{1440}$

Estimating Exposure

Preferred method: kitchen concentration to personal exposure ratio

The primary method to estimate personal exposure is to multiply the 24-hour mean concentration by an exposure ratio (R). The exposure ratios are ideally location-specific, though default estimates are suggested as those used in the 2010 Global Burden of Disease Study (0.742 for women, 0.628 for young children, 0.450 for men) (Smith et al., 2014). The personal exposure based on this ratio (E_r) is defined as follows (Equation 3):

Equation 3. $E_r = C_kR$, with the condition that $E_r \geq C_b$

Advanced option: time-activity ratios

A second, more advanced approach is also available, for which exposures are estimated based on weighting the amount of time a person spends in the kitchen (t_k) and that outside of the kitchen. Exposure outside of the kitchen is assumed to be equal to the background ambient concentration. The personal exposure based on time spent in the kitchen (E_t) is defined as follows (Equation 4):

Equation 4. $E_t = C_k\left(\frac{t_k}{1440}\right) + C_b\left(\frac{1440 - t_k}{1440}\right)$

Note that this second approach should only be used if data collection including accurate time-activity patterns has occurred. This option is given as an "Advanced Option" in the model and is only recommended for groups with expertise in collection and application of this type of data, which have collected accurate empirical data.

The main approach (based on the ratio of kitchen to personal exposure) is recommended and can be used with a default concentration if none is known locally.

Finally, relative risk for various health endpoints can be estimated by using available integrated exposure risk curves. Here we have included an estimate for acute lower respiratory infections (ALRI), though others such as ischemic heart disease and lung cancer can also be applied. The ALRI risk curve used here is from the 2010 Global Burden of Disease Study (Burnett et al., 2014; Smith et al., 2014), which each exposure assigned the relative risk associated with that exposure concentration on the ALRI risk curve.

Population assessments of indoor air quality

To help represent the variability of conditions in real-world homes, the model described above is run through a Monte Carlo simulation. A Monte Carlo simulation is a statistical approach to probabilistic modelling, for which input parameters are randomly selected from predetermined distributions and run through the model (Binder and Heermann, 2010). The model then produces a distribution of outputs, in this case estimated concentrations of PM2.5 or CO. For the HOMES model, the Monte Carlo approach accounts for varying the input parameters such as kitchen volume, stove use time, and kitchen volume, according to the variation that has been observed for a given context or population. With the input information varying according to the population of households being considered, the outputs (e.g. kitchen concentrations) are then described as distributions. Figure 3 illustrates this approach, where the model repeatedly pulls values from distributions of cooking time, room volume, and air change rate, inputs them into the model with a given emissions rate. It repeats this process 5,000 times and outputs the distribution of estimated pollution levels in a hypothetical population of households. By applying a Monte Carlo approach to the HOMES model, more realistic results are generated which are specifically tailored to the unique distributions of kitchen volumes, emissions performance, cooking times, and air change rates for a given context.

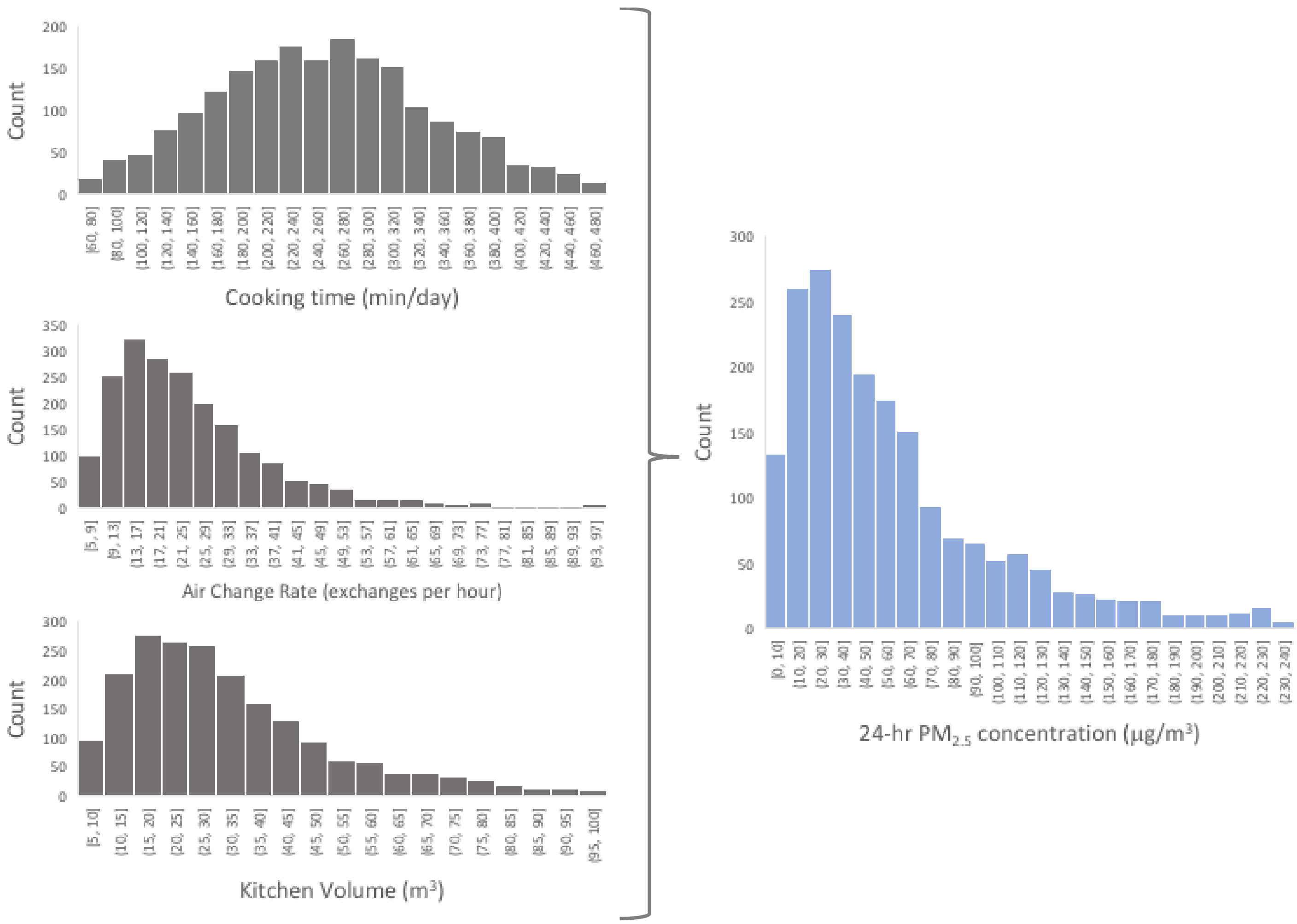

Figure 3. Illustrative input distributions (left) are used to iteratively select values for the model, which then produces a distribution of predicted kitchen pollutant concentrations (right)

Note that in the example in Figure 3, only one discrete emissions source is being modelled to provide a simplified illustration of the Monte Carlo approach (it is possible to model up to three emissions sources in the HOMES model). The HOMES model includes input distributions of multiple emissions sources, fixed contributions to indoor concentrations from ambient air pollution, as well as calculations to estimate exposure and ALRI relative risk.

3. Running the HOMES model

Guidance related to programmatic implementation of the model is provided at http://www.who.int/airpollution/household/interventions/chest-module4/en/. That guidance is designed to give context about how this model fits within a program or government standards framework. Here, specific step-by-step instructions are provided on how to run the model.

Entering input parameters

To run the HOMES model, the user enters the distributional statistics (arithmetic mean and standard deviation) for the given model inputs. The model inputs and considerations for their determination are provided in Table 1 below. Considerations include important context and basic guidance for their determination, while detailed protocols for data collection for each of the parameters is provided separately in documentation available at http://www.who.int/airpollution/household/interventions/chest-module4/en/.

Table 1: Input parameters and considerations for their distributions

Input Parameter	Considerations
Air change rate (air changes per minute)	Air change rates for a given context can be measured directly or based on literature values when available. Field studies involve measuring the rate at which a tracer gas decreases in concentration, which can then be converted into an air change rate. The distribution for this parameter is set as a lognormal shape as this is what has generally been observed in previously collected data. Protocol guidance for this measurement is provided at online in the document *WHO Household Multiple Emission Sources (HOMES) Model: Input Parameter Protocol – Air Change Rate.* The *Database of input variables for the WHO Household Multiple Emission Sources (HOMES) and Performance Targets (PT) Models* includes air change rates specifically for this model and can be found online.
Kitchen volume (m^3)	Kitchen volumes for a given context can be measured directly or based on literature values when available. Field studies involve measuring the geometries of kitchens. The distribution for this parameter is set as a lognormal shape as this is what has generally been observed in previously collected data. Protocol guidance for this measurement is provided online in the document *WHO Household Multiple Emission Sources (HOMES) Model: Input Parameter Protocol – Kitchen Volume.* The *Database of input variables for the WHO Household Multiple Emission Sources (HOMES) and Performance Targets (PT) Models* includes kitchen volumes specifically for this model and can be found online.

Device usage time (min/day)	Device usage times for a given context can be measured directly or based on literature values when available. Studies of direct usage typically involve measuring stove temperature over time. Time use estimates can also be made via participant recall, although this method is generally thought to be less accurate and objective. The distribution for this parameter is set as a normal shape as this is what has been observed in previously collected data. Protocol guidance for this measurement is provided online in the document *WHO Household Multiple Emission Sources (HOMES) Model: Input Parameter Protocol – Stove Usage.* The *Database of input variables for the WHO Household Multiple Emission Sources (HOMES) and Performance Targets (PT) Models* includes stove use times specifically identified for use in this model and can be found online.
Emissions rate	Emissions rates can be based on laboratory or field-based studies, though care should always taken to understand the limitations of the data. For example, laboratory-based estimates are likely to underestimate emissions performance of devices in everyday use in the home, as the laboratory tests are generally conducted under relatively idealized conditions. Data from field-based studies, while likely more accurate, may also be limited due to sample size, less precise instrumentation, and factors that may affect emissions performance such as seasonal changes and different fuel types/conditions. The distribution for this parameter is set as a lognormal shape as this is what has generally been observed in previously collected data. The largest repository of emissions data can be found at http://catalog.cleancookstoves.org/. The online *Database of input variables for the WHO Household Multiple Emission Sources (HOMES) and Performance Targets (PT) Models* includes emission rates specifically identified for use in this model. Additional guidance on this parameter can be found in Edwards et al., 2014.
Fraction of emissions entering room	This parameter is 1 for open fire stoves which vent directly into the kitchen. It can also be set at one for chimney stoves when the fugitive emission rates are measured directly and entered into the model. When fugitive for chimney stoves are not known but estimates of a chimney or vented stove's capture efficiency are applied (either from default or measured values), then the distribution of the estimated capture efficiency can be entered as the fraction of emissions entering the room. The distribution for this parameter is fixed when entered as 1, and as a lognormal shape when set at other values. Protocol guidance for this measurement is provided online in the document *WHO Household Multiple Emission Sources (HOMES) Model: Input Parameter Protocol – Indirect Measurements*.

Background ambient concentrations ($\mu g/m^3$)	Background concentrations can be measured or obtained from literature-based values. Measurements of background concentrations are best if conducted within communities typical of the area interest. This parameter is entered as a discrete input for simplicity. If only the impact of a single or multiple emission sources is desired, then 0 $\mu g/m^3$ can be entered for the background concentration. While entering 0 $\mu g/m^3$ is useful for isolating source-specific impacts, it is recommended to enter the best available estimate for background concentrations to better understand potential impacts on kitchen concentrations and exposures. Additional guidance on this parameter can be found online in the document *WHO Household Multiple Emission Sources (HOMES) Model: Input Parameter Protocol – Indirect Measurements*.
Personal exposure to kitchen concentration ratio	The ratio of exposure to kitchen concentrations is used to estimate personal exposure based on kitchen concentrations. Estimates for this ratio can be measured directly or based on literature values as provided above. This value is entered as a discrete input in the model for simplicity. Note that the model will need to be re-run for with different ratios if being run for women, men, and children, respectively, and if these groups have different ratios of personal exposure to kitchen concentration. Additional guidance on this parameter can be found online in the document *WHO Household Multiple Emission Sources (HOMES) Model: Input Parameter Protocol – Indirect Measurements*.
Time spent in kitchen	This option is only recommended for more advanced users of the model as it requires collection of accurate time-activity patterns. Groups with expertise in collection and application of this type of data are best suited to use this approach. This parameter is entered discretely into the model for simplicity (fixed at the value entered). Additional protocol guidance for collecting data on this parameter can be found at online in the document *WHO Household Multiple Emission Sources (HOMES) Model: Input Parameter Protocol – Indirect Measurements*.

Once specific values for the model are determined, they are entered into the “Inputs” page for the HOMES model. Step-by-step instructions for entering the inputs are provided here with an example screenshot provided in Figure 3:

1. Navigate to the inputs page by selecting the “Inputs” tab on the left-hand menu.
2. Enter the distributional statistics (mean and standard deviation) for air change rate and kitchen volume. For simplicity, the shapes of the distributions have been set as lognormal.
3. Enter the ambient concentration.
4. Select the number of emissions sources (1-3)
5. Use the slider to select the ratio of personal exposure to kitchen concentration (recommended option).

6. Users may select the advanced option to enter the time-spent-in-kitchen parameter (only recommended for users with experience in collecting this type of data, who have this data available for a local context).
7. Enter the distributional statistics (mean and standard deviation) for each emission source, which includes the emission rates, cooking time, and fraction of emissions which enter the room. For simplicity, the shape of the distribution emission rates is lognormal and that for cooking time is normal. The percent of emissions mixing in the room is fixed at 100% when set at 100%; otherwise the distribution is lognormal if set at a value of less than 100%.
8. Once all of the inputs are entered, click on the "Run the Model" tab on the left navigation bar to start the Monte Carlo simulation. Note that it will take a few minutes for the model to run as it will be doing 5,000 simulations.

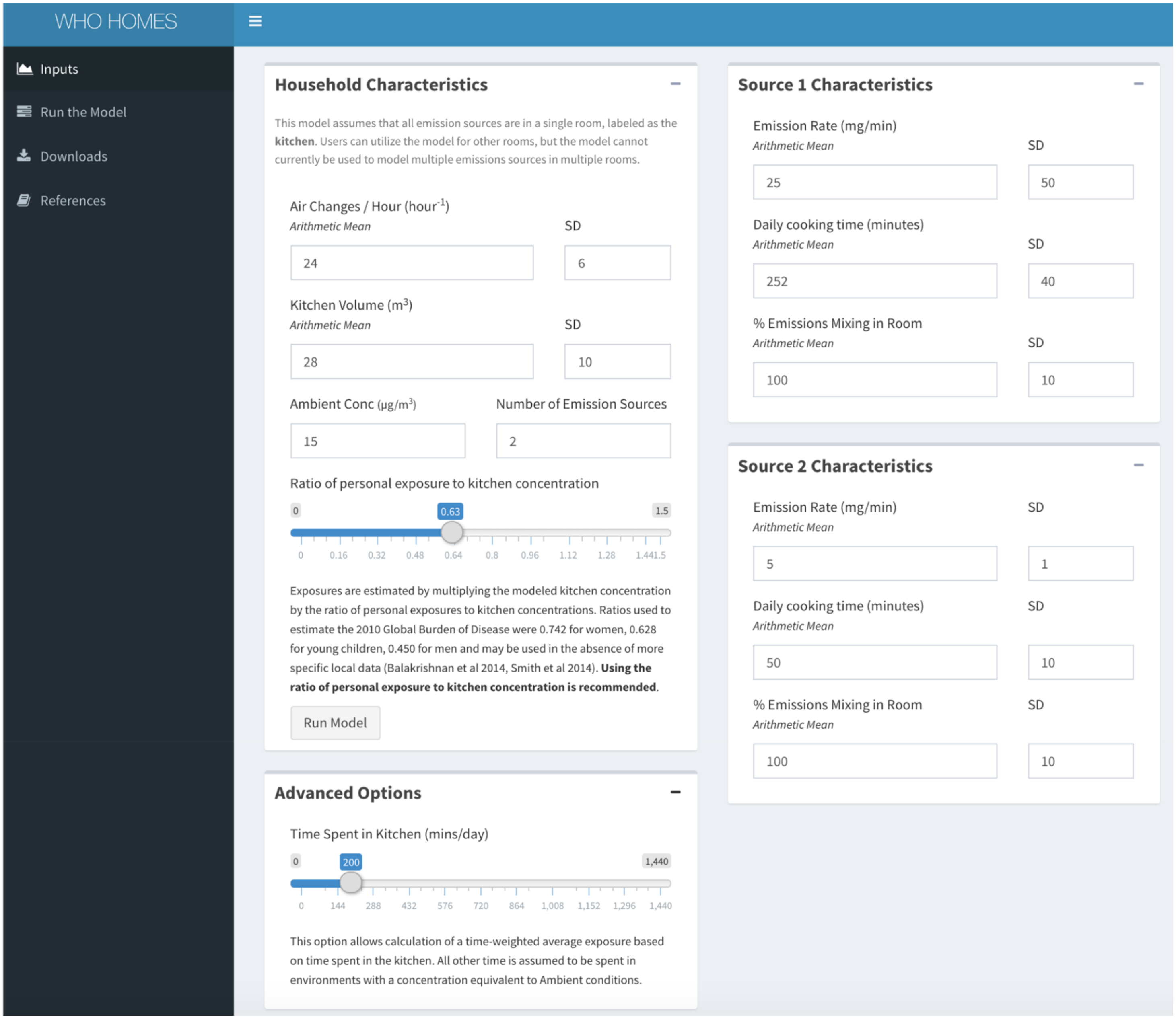

Figure 4. Example of the inputs for the WHO HOMES model. This example shows the inputs for a room with two emission sources.

Model outputs

Once the model has completed running, the output page will then show the estimated distribution of 24-hour mean pollutant concentrations for the kitchen and personal exposures based on the inputs, with the mean, maximum, and standard deviation values for the estimated 24-hour concentrations (see Figure 5).

Three concentration estimates are provided. The first is the concentration modelled in the kitchen. The second is the estimated exposure concentrations based on the ratio of personal to kitchen concentrations and the time spent in kitchen, respectively. Note that there is a third concentration estimate that can be calculated based on the time spent in kitchen, which is only available in the advanced output. The two different exposure estimates will differ because they are two different approaches which make different assumptions about estimating exposure.

The output also includes the relative risk of acute lower respiratory infections (ALRI) that are associated with the given exposure estimates, based on exposure-risk curves from the Household Air Pollution Comparative Risk Assessment in 2010 (Smith et al., 2014) and related integrated-exposure response curves (Burnett et al., 2014).

WHO air quality targets and guidelines are also provided for reference.

Note that these exposure-risk curves are being updated and may change in future versions of the model. Additionally, the air quality guidelines and health risks are not applicable if the user is inputting an air pollutant other than $PM_{2.5}$.

Detailed information on each of the model runs and inputs can be downloaded via the "Downloads" link on the left-hand side of the window. These files include the specific values input for each simulation, and more detailed graphs of the input and output distributions.

Figure 5. Example output from the HOMES model. This example shows the output for a room with two emission sources. The graph in the upper left shows example concentrations of a selection of the model

simulations for one of the three cooking events. The upper right-hand graph shows the modelled distribution of kitchen concentrations resulting from the simulations.

4. Acknowledgements

The HOMES model was developed by Berkeley Air Monitoring Group for the World Health Organization. Please contact householdenergy@who.int with any questions.

We are grateful for the extensive input and support from organizations and individuals. The initial version of this model (which was based on the PT model) was conceptualized by Professor Kirk Smith (University of California Berkeley) and Dr. Nicholas Lam (Berkeley Air Monitoring Group; University of California Berkeley). Its application for the WHO Guidelines for Indoor Air Quality: Household Fuel Combustion was aided by Professor Rufus Edwards (University of California, Irvine), Professor Mark Nicas (University of California, Berkeley), and Professor Lidia Morawska (Queensland University of Technology). We also thank Professor Daniel Pope and Professor Kalpana Balakrishnan for graciously hosting pilot exercises using the web version of the models at their research sites in Cameroon and India, respectively.

5. References

Apple, J., Vicente, R., Yarberry, A., Lohse, N., Mills, E., Jacobson, A., and Poppendieck, D. (2010). Characterization of particulate matter size distributions and indoor concentrations from kerosene and diesel lamps. Indoor Air *20*, 399–411.

Binder, K., and Heermann, D.W. (2010). Monte Carlo simulation in statistical physics: an introduction (Heidelberg: Springer).

Bond, T.C., Zarzycki, C., Flanner, M.G., and Koch, D.M. (2011). Quantifying immediate radiative forcing by black carbon and organic matter with the Specific Forcing Pulse. Atmos Chem Phys *11*, 1505–1525.

Burnett, R.T., Pope, C.A., III, Ezzati, M., Olives, C., Lim, S.S., Mehta, S., Shin, H.H., Singh, G., Hubbell, B., Brauer, M., et al. (2014). An Integrated Risk Function for Estimating the Global Burden of Disease Attributable to Ambient Fine Particulate Matter Exposure. Environ. Health Perspect.

Edwards, R., Karnani, S., Fisher, E.M., Johnson, M.A., Naeher, L., and Smith, K.R. (2014). WHO Guidelines for Indoor Air Quality: Household Fuel Combustion - Emissions of Health-Damaging Pollutants from Household Stoves.

Hellweg, S., Demou, E., Bruzzi, R., Meijer, A., Rosenbaum, R.K., Huijbregts, M.A.J., and McKone, T.E. (2009). Integrating Human Indoor Air Pollutant Exposure within Life Cycle Impact Assessment. Env. Sci Technol *43*, 1670–1679.

ISO (2012). IWA 11:2012: Guidelines for evaluating cookstove performance.

Jarod Maggio (2013). Kitchen 2.0- Indoor Air Quality Modeling Utilizing Computational Fluid Dynamics for Application in Developing Countries. (Kirkland, WA).

Johnson, M. (2011). Modeling Indoor Air Pollution Concentrations from Stove Emissions Using a Monte Carlo Single-Box Model.

Johnson, M.A., and Chiang, R.A. (2015a). Quantitative Guidance for Stove Usage and Performance to Achieve Health and Environmental Targets. Environ. Health Perspect.

Johnson, M.A., and Chiang, R.A. (2015b). Quantitative Stove Use and Ventilation Guidance for Behavior Change Strategies. J. Health Commun. *20*, 6–9.

Johnson, M.A., Edwards, R., Morawska, L., Smith, K.R., and Nicas, M. (2014). WHO Guidelines for Indoor Air Quality: Household Fuel Combustion - Model for linking household energy use with indoor air quality.

Lewis, J.J., and Pattanayak, S.K. (2012). Who Adopts Improved Fuels and Cookstoves? A Systematic Review. Env. Health Perspect.

L'Orange, C., Leith, D., Volckens, J., and DeFoort, M. (2015). A quantitative model of cookstove variability and field performance: Implications for sample size. Biomass Bioenergy *72*, 233–241.

Masera, O.R., Saatkamp, B.D., and Kammen, D.M. (2000). From Linear Fuel Switching to Multiple Cooking Strategies: A Critique and Alternative to the Energy Ladder Model. World Dev. *28*, 2083–2103.

McCracken, J.P., and Smith, K.R. (1998). Emissions and efficiency of improved woodburning cookstoves in highland Guatemala. Env. Int. *24*, 739–747.

Nicas, M. (2009). A Three-Zone Model for Welding Fume Concentrations. J. Occup. Environ. Hyg. *6*, D69–D71.

Prasad, K.K., Sangen, E., and Visser, P. (1985). Woodburning Cookstoves. In Advances in Heat Transfer, J.P. Hartnett, and J. Thomas F. Irvine, eds. (Orlando, FL: Academic Press), pp. 159–317.

Ruiz-Mercado, I., Masera, O., Zamora, H., and Smith, K.R. (2011). Adoption and sustained use of improved cookstoves. Energy Policy *39*, 7557–7566.

Schare, S., and Smith, K.R. (1995). Particulate emission rates of simple kerosene lamps. Energy Sustain. Dev. *2*, 32–35.

Smith, K.R., Aggarwal, A.L., and Dave, R.M. (1983). Air pollution and rural biomass fuels in developing countries: A pilot village study in India and implications for research and policy. Atmospheric Environ. 1967 *17*, 2343–2362.

Smith, K.R., Bruce, N., Balakrishnan, K., Adair-Rohani, H., Balmes, J., Chafe, Z., Dherani, M., Hosgood, H.D., Mehta, S., Pope, D., et al. (2014). Millions Dead: How Do We Know and What Does It Mean? Methods Used in the Comparative Risk Assessment of Household Air Pollution. Annu. Rev. Public Health *35*, 185–206.

USEPA (2000). Simulation Toolkit of Indoor Air Quality and Inhalation Exposure (IAQX) (Research Triangle Park, NC: United States Environmental Protection Agency).

WHO (2006). WHO guidelines for particulate matter, ozone, nitrogen dioxide and sulfur dioxide (Geneva: World Health Organization Press).

WHO (2010). WHO guidelines for indoor air quality: selected pollutants (Bonn: World Health Organization Regional Office for Europe).

WHO (2014). WHO Guidelines for Indoor Air Quality: Household Fuel Combustion (Geneva: World Health Organization).