Laboratorio de Innovación y Evaluación de Estufas de Biomasa

Universidad Nacional Autónoma de México

Estimating Kitchen $PM_{2.5}$ and CO Concentrations out of Stove Emissions: The case of Mexican Plancha-type Stoves

Víctor Ruiz
Omar Masera

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Summary

This report is the first attempt to predict CO and $PM_{2.5}$ kitchen concentrations in Mexican villages out of indoor stove pollutant emission data. To do this, we use the single-box model developed by Johnson (2008) and installed a double-hood to measure fugitive emissions (defined here as the fraction of total stove emissions that remain indoor) from the stoves. Model inputs –such as kitchen volume, air exchange rates and cooking time- come from field data and represent a typical rural house in Michoacan, Central Mexico. CO and $PM_{2.5}$ emission rates and fugitive emissions were measured in the Lab and obtained for the four improved cookstoves most disseminated in Mexico (Patsari, ONIL, Ecostufa and Mera-Mera).

Average fraction of fugitive emissions were estimated in 5±3 (ranged from 0-15%) for $PM_{2.5}$ emissions and 1±1 (ranged from 0-8%) for CO emissions. These values are much lower than those suggested by the WHO guidelines (25±10% for $PM_{2.5}$). The estimated average annual $PM_{2.5}$ concentrations ranged from 10 to 19 $\mu g/m^3$ depending on the stove, all are below the 35 $\mu g/m^3$ Interim target-1 suggested by WHO. The estimated average CO concentrations (24-h) ranged from 0.02 to 0.10 $\mu g/m^3$ depending on the stove, all are well below the 7 $\mu g/m^3$ (AQG) suggested by WHO.

Using a Monte Carlo simulation (n=10,000) the modeled distributions of average $PM_{2.5}$ annual kitchen concentrations result in between 94% and 99% of the cases meeting the WHO Interim target-1 (35 $\mu g/m^3$), depending on the stove. On the other hand, all the modeled distributions for all the stoves met the 24-h CO AQG (7 mg/m^3).

1. Introduction

Chimney-stoves have been widely disseminated in Mexico as they are well suited to local cooking traditions and are widely accepted in local communities (Medina *et al*, 2016). More than 600,000 chimney-stoves have been disseminated in Mexico between 2007 and 2012 (Berrueta *et al*, 2014).

Currently there is a big discussion about the actual reduction in IAP pollutant concentrations that can be achieved with woodburning stoves. So far the discussion has centered on stoves without a flue, which do not represent well the situation of chimney-stoves.

Given the difficulties to extensively measure IAP levels in-situ, modeling approaches have been used to predict pollutant kitchen concentrations out of data on stove emission rates (Johnson, 2008). To provide accurate estimates the models need reliable inputs, which involve collecting local data.

One of the key parameters that need to be measured for adequately estimating the impact of chimney stoves in IAP is the fraction of pollutants produced by the stove that enters the kitchen *"f"* (i.e., the pollutants that do not exit through the chimney but leak through the fuel entry, or from other parts of the stove). This fraction, times total stove emissions is known as "fugitive emissions" and regrettably very little is known about their actual weight regarding total stove emissions. For example, the WHO roughly assumed that for chimney stoves, *f* ranges from 1-50% with a mean of 25% and standard deviation of 10% (Jonhson, 2014). Other authors consider that for a well-functioning chimney the value of *f* for CO is 10% (Smith *et al*, 2009).

Accurately estimating *f* is key to properly estimate the contribution of stoves to indoor air pollution. As can be seen from Figure 1, the indoor pollutant concentration within a kitchen is the result of: the fugitive emissions from the stove, the emissions that may re-infiltrate through the chimney of the same stove, and through ambient pollutants (i.e., pollutants that come from other external sources and enter the kitchen). Therefore, just measuring the IAP concentration will give a value that already compounds these 3 sources. To avoid this problem, we set up a double hood (see Methods section) that allows measuring *f* without the interference of external sources.

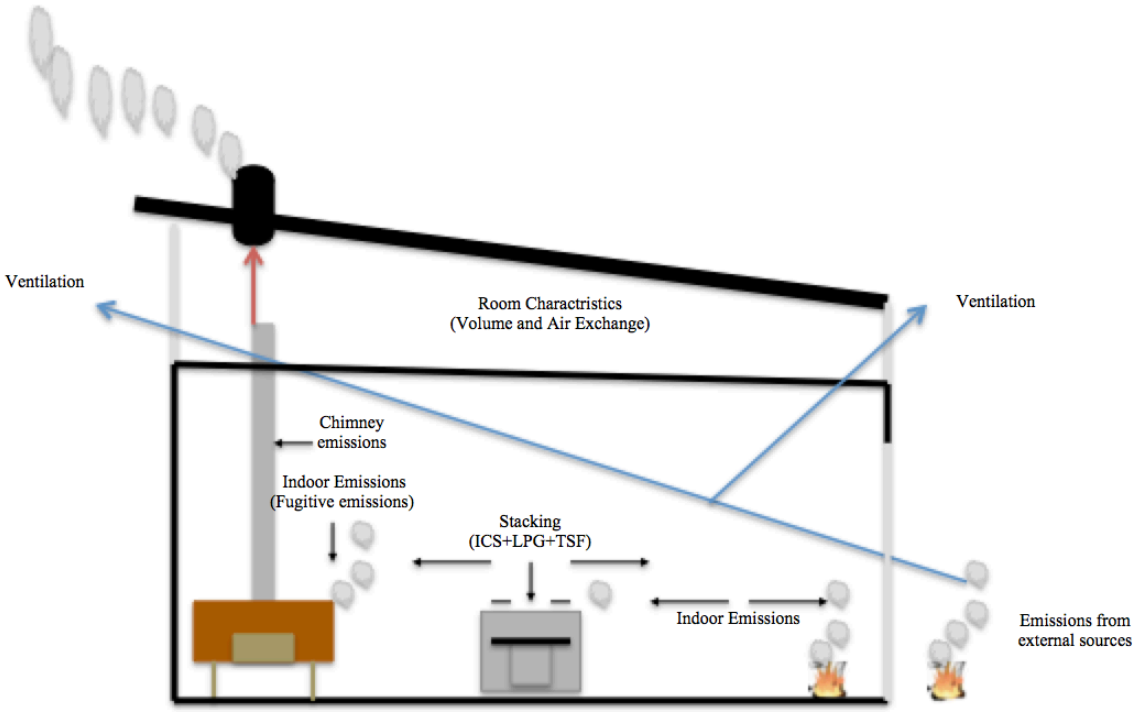

Figure 1. Contribution of different sources to indoor air pollution. Source: Modified from WHO, 2014.

There is also a large uncertainty about other important parameters, such as kitchen volumes, ventilation rates and stove emission rates, which need to be measured locally.

This report presents a first attempt to predict CO and $PM_{2.5}$ kitchen concentrations within Mexican villages. out of stove emissions data. We use the single-box model developed by Johnson (2008). Model inputs –such as kitchen volume, air exchange rates and cooking time- come from field data and represent a typical rural house in Michoacan, Central Mexico. CO and $PM_{2.5}$ total and fugitive emission rates were measured with a double-hood at the lab for the four improved cookstoves most disseminated in Mexico (Patsari, ONIL, Ecostufa and Mera-Mera).

2. Methods

2.1 Monte Carlo Single Box-Model

The single Box-Model predicts room concentrations based on stove emissions and kitchen characteristics.

The model is described mathematically as:

$$C_t = \frac{Gf}{\alpha V}(1 - e^{-\alpha t}) + C_o(e^{-\alpha t}) \quad (1)$$

Where,
C_t= Concentration of pollutant within the kitchen at time t (mg/m^3);
G= Emission rate (mg/min);
f= fraction of fugitive emissions (measured as a fraction of total stove emissions);
α= Nominal air exchange rate (min^{-1});
V= Kitchen volume (m^3);
t= Time (min).

Conventionally, kitchen pollutant concentration "C" is expressed as the sum of fugitive emissions (f * G) from the stove plus the re-infiltration of ambient pollutants. However, in this report we are not including the re-infiltration term as we wanted to measure the specific contribution of the stoves. We assume that the chimney has been properly set up so the smoke exiting at the end of the chimney does not re-enter the house. Other sources of re-infiltration involving external sources (such as smoke from neighbor houses, additional stoves, burning of organic wastes or agriculture residues, etc.) are very location specific and thus will need to be estimated case by case.

A Monte Carlo approach was used to predict distributions $PM_{2.5}$ and CO concentrations. 10,000 simulations of a cooking day were run. The probability distributions of each variable was selected before running the Monte Carlo simulation and the initial kitchen concentration was set to zero.

2.2 Model Inputs

All the model inputs used are specific to Mexican conditions.

a- Field Parameters

We obtained all model field parameters from Mexican Villages located within the Purepecha Region of Michoacan. The average, min and max values for each parameter are shown in Table 1. The kitchen volume was measured for 627 typical houses. The tracer decay was measured with CO at 30 ppm in a simulated kitchen with the same volume of typical kitchens to determine the nominal air exchange rate (n=31 measurements). Measurements were taken in different days, one measurement every hour, and assuming the lowest annual wind speeds for the location. One of the limitations of making repeated measurements in the same kitchen instead of measuring air nominal air exchange rates in different local houses is that the variability of the date is reduced.

Cooking time represents the period of time when the cooker uses the stove (n=30) and is measured in minutes per day (Table 1).

Table 1. Model inputs.

Parameter	Unit	Mean	SD	Min	Max
Kitchen volume	m^3	41	20	5	97
Cooking time	min	259	123	60	480
Nominal air exchange rate	h^{-1}	60	13	36	90
Emission rate (total)					
ONIL	$PM_{2.5}$ (mg min^{-1})	55	32	20	127
	CO (mg min^{-1})	606	338	134	1184
Ecostufa	$PM_{2.5}$ (mg min^{-1})	79	52	18	204
	CO (mg min^{-1})	936	589	149	1820
Mera-Mera	$PM_{2.5}$ (mg min^{-1})	78	48	25	186
	CO (mg min^{-1})	1264	554	436	2141
Patsari	$PM_{2.5}$ (mg min^{-1})	54	21	18	88
	CO (mg min^{-1})	1656	973	273	3397
Chimney-Stoves tested	$PM_{2.5}$ (mg min^{-1})	66	41	18	204
	CO (mg min^{-1})	1116	749	134	3397
Fraction of fugitive emissions (as a fraction of total emissions *"f")*					
ONIL	$PM_{2.5}$ (Unitless)	0.05	0.03	0.00	0.11
	CO (Unitless)	0.02	0.02	0.00	0.08
Ecostufa	$PM_{2.5}$ (Unitless)	0.06	0.04	0.01	0.15
	CO (Unitless)	0.01	0.01	0.00	0.03
Mera-Mera	$PM_{2.5}$ (Unitless)	0.03	0.02	0.01	0.08
	CO (Unitless)	0.01	0.01	0.00	0.03
Patsari	$PM_{2.5}$ (Unitless)	0.07	0.03	0.00	0.13
	CO (Unitless)	0.01	0.00	0.00	0.01
Chimney-Stoves tested	$PM_{2.5}$ (Unitless)	0.05	0.03	0.00	0.15
	CO (Unitless)	0.01	0.01	0.00	0.08

Note: All the input parameters, showed a normal distribution.

b- Lab Parameters

The WBT protocol version 4.2.4 was used to determine emission parameters of four Plancha-Stoves models with chimney (Patsari, ONIL, Mera-Mera and Ecostufa).

A double hood was set up to capture both chimney and fugitive emissions (Figure 2), so the real fraction of fugitive emissions entering the kitchen (*f*) was calculated (Table 1).

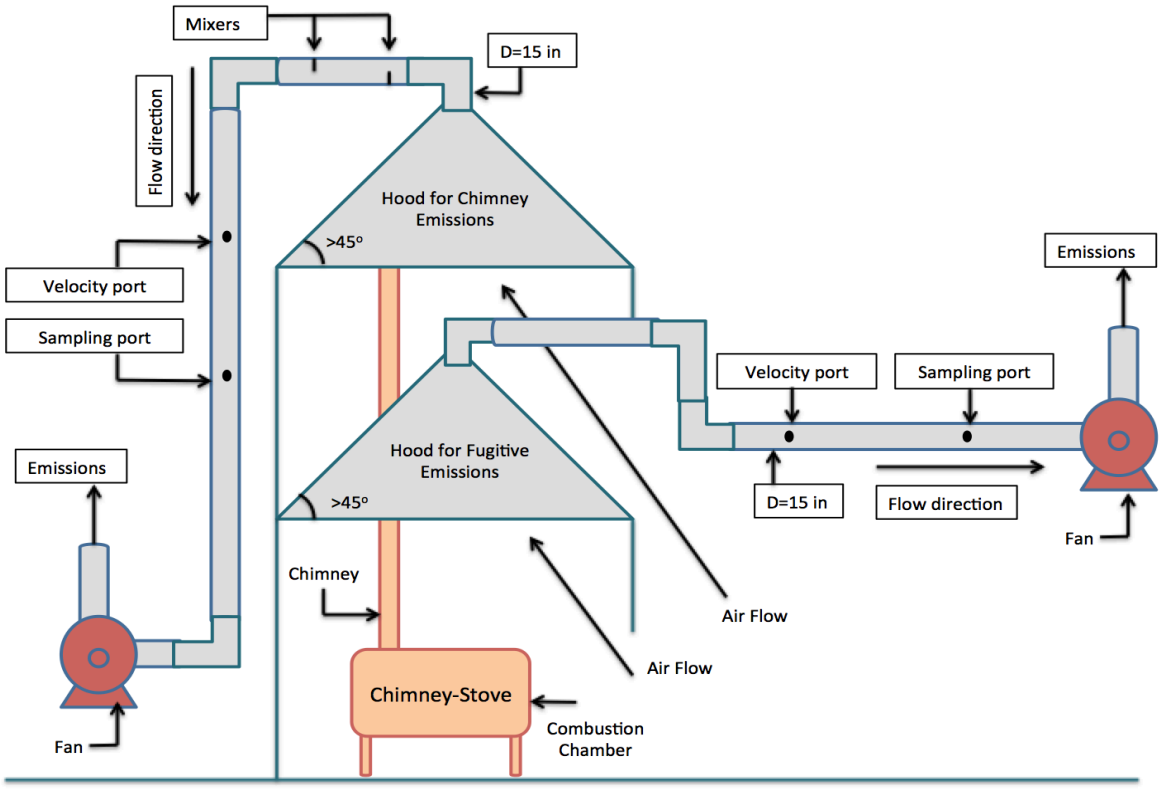

Figure 2. Diagram of double hood for measuring fugitive emissions and chimney emissions.

LINEB staff applied the Quality Assurance Plan that was developed with the support of this grant. The equipment used to measure pollutant emissions is shown in Table 2.

Table 2. Equipment Description.

Emissions	Equipment	Pollutant	Equipment Calibration/measure in real time
Fugitive	Qtrak & Velocic Calc (TSI)	CO and $PM_{2.5}$	Yes/Yes
Chimney	LEMS (Aprovecho Research)	CO and $PM_{2.5}$	Yes/Yes

3. Results and discussion

3.1 Model Outputs

Table 3 presents summary statistics and the percentage of simulations meeting the respective WHO AQGs concentrations of $PM_{2.5}$ (annual average concentrations, Interim Target 1) and CO (AQG 24-h). The average fraction of fugitive emissions was ranged from 0-15% for $PM_{2.5}$ emissions and 0-8% for CO emissions. These values are much lower than those suggested by the WHO guidelines (25±10% for $PM_{2.5}$). For $PM_{2.5}$ *f* ranged from 3% for Mera-Mera to 7% for Patsari. For CO *f* ranged from 1% for Patsari to 2% for ONIL.

The estimated average $PM_{2.5}$ concentrations ranged from 10 to 19 µg/m^3 depending on the stove, all are below the 35 µg/m^3 Interim Target-1 suggested by WHO. The estimated average CO concentrations (24-h) ranged from 0.02 to 0.10 µg/m^3 depending on the stove, all are well below the 7 µg/m^3 (AQG) suggested by WHO (Figure 3 and 4).

Table 3. Summary statistics of model output and percent of simulations meeting WHO Air Quality Guidelines for four different stoves.

	ONIL	Ecostufa	Mera-Mera	Patsari	Chimney-Stoves tested
Particular matter model output					
Mean (µg/m^3)	10	17	12	19	15
Median (µg/m^3)	9	15	10	17	13
Standard deviation	6	0	7	11	9
10th percentile (µg/m^3)	5	9	5	9	7
90th percentile (µg/m^3)	17	28	20	31	25
Percent of simulation meeting WHO $PM_{2.5}$ guideline					
24-h Interim Target-1 (75 µg/ m3)	100%	100%	100%	100%	100%
24-h AQG (25 µg/ m3)	97%	87%	96%	81%	91%
Annual Interim Target-1 (35 µg/ m3)	**99%**	**96%**	**99%**	**94%**	**97%**
Annual AQG (10 µg/ m3)	58%	17%	46%	13%	30%
Carbon Monoxide model output					
Mean (mg/m^3)	0.06	0.02	0.10	0.05	0.06
Median (mg/m^3)	0.05	0.02	0.09	0.05	0.05
Standard deviation	0.04	0.01	0.06	0.03	0.04
10th percentile (mg/m^3)	0.02	0.01	0.04	0.02	0.02
90th percentile (mg/m^3)	0.10	0.04	0.16	0.09	0.11
Percent of simulation meeting WHO carbon monoxide guideline					
24-h AQG (7 mg/m3)	**100%**	**100%**	**100%**	**100%**	**100%**

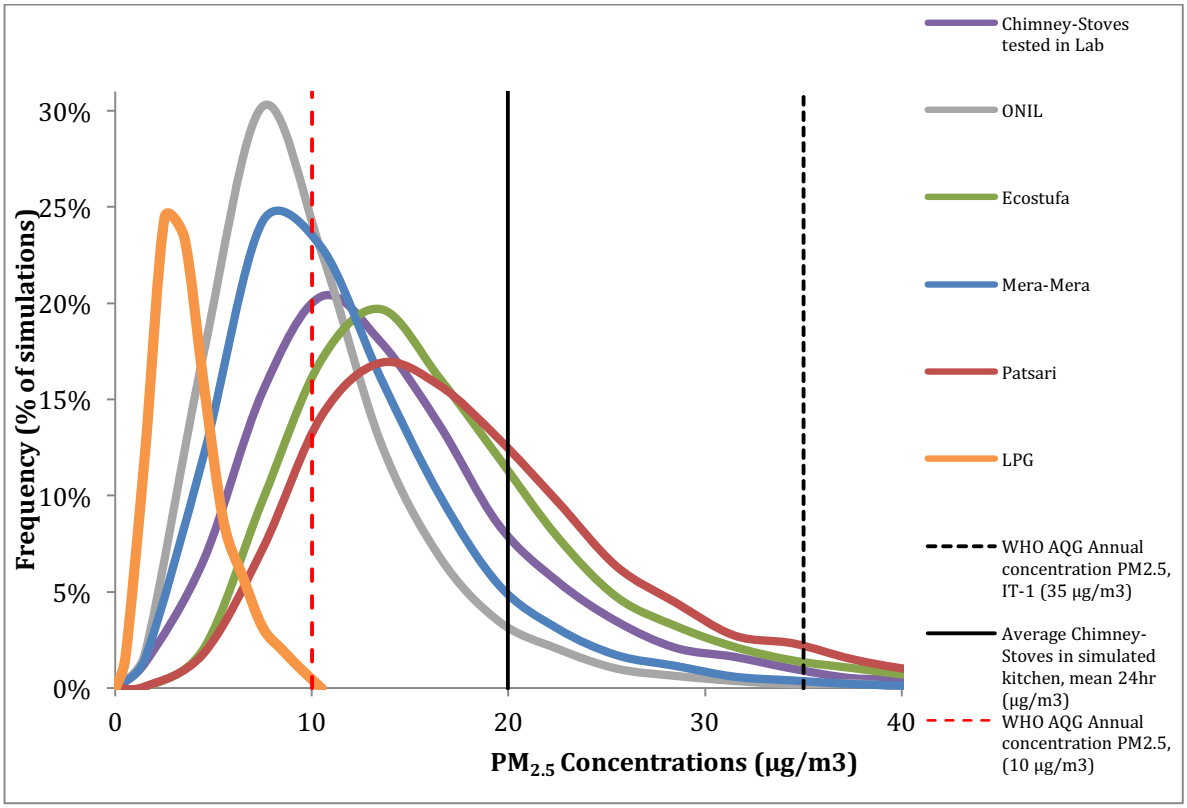

Figure 3. Model output distributions of $PM_{2.5}$ concentrations. Note: The line for Chimney stoves in Lab represents the mean of the distribution shown with the purple line.

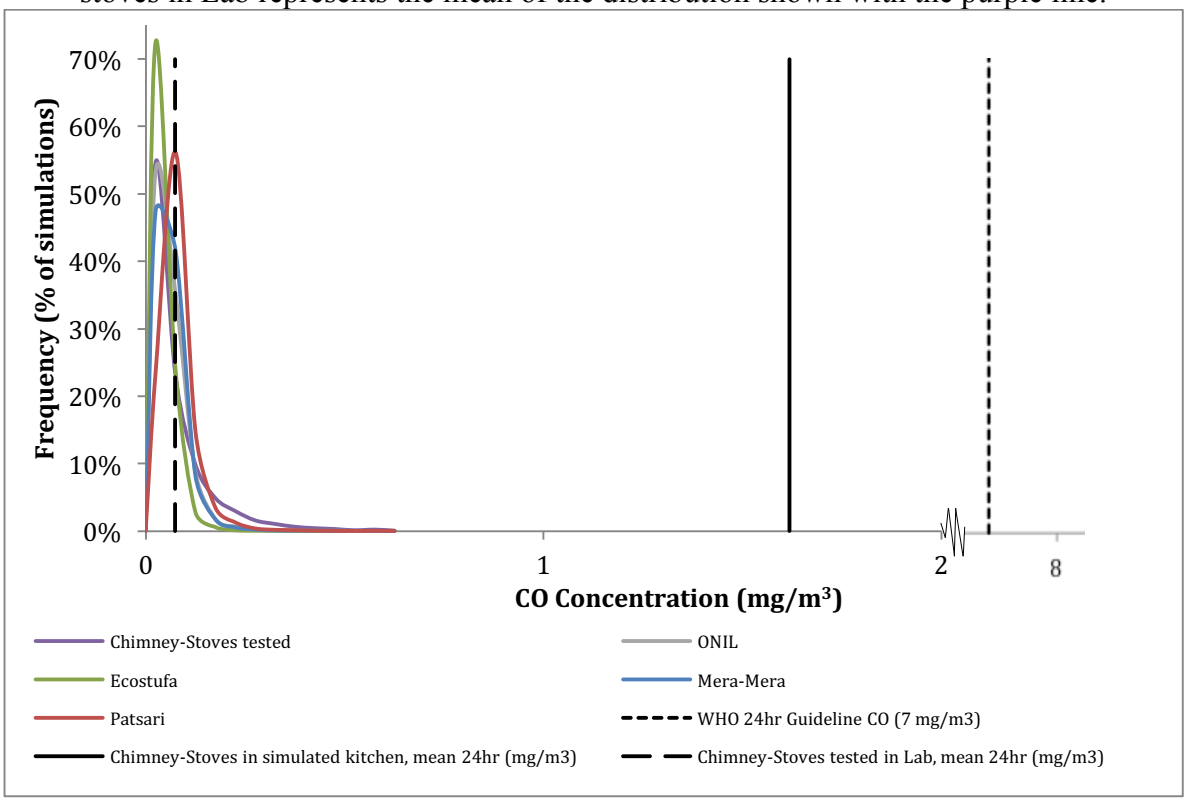

Figure 4. Model output distributions of CO concentrations. The line for Chimney stoves in Lab represents the mean of the distribution shown with the purple line.

3.2 Assumptions

As stated previously, the simulation conducted in the single box model does not include re-infiltration of outside sources. This allows us to estimate the contribution of fugitive emissions coming from the stove alone. Also, it should be noted that in the field, re-infiltration is highly variable, depending on the kitchen design, flue height, and the vicinity of houses within the villages.

We also assume that the model input parameter distributions correspond to a large population, and that there is perfect air mixing –i.e., there is no stratification of the pollutants.

3.3 Box-Model validation

Figure 3 and 4 show average IAP concentrations of $PM_{2.5}$ and CO measured in a series of tests conducted in a simulated kitchen located in the same place were the present measurements were taken. In this case the Patsari and ONIL stoves were tested. Measurements were conducted with a Langan CO Measurer and a MiniVol PM Portable Sampler for $PM_{2.5}$ (Blanco *et al* 2012). The mean $PM_{2.5}$ concentrations obtained were 20 $\mu g/ m^3$ and the mean CO concentrations 1.6 mg/m^3. In both cases the mean concentrations of CO and $PM_{2.5}$ are below those recommended by the WHO and the AQG. The average of the combination of stoves tested (also shown as a line in Figure 3 and 4) is a bit below the values obtained in the simulated kitchen, particularly for CO. However, in general there is good agreement between the measured and modeled concentrations. These results and the pollutant distributions from the Monte Carlo simulation confirm that when properly operated chimney stoves could reach IWA Tier 4 both regarding PM and CO indoor air pollution concentrations.

Acknowledgements

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4. References

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Annex A. Steps to run Monte Carlo Single Box-Model

Purpose: This document outlines steps to run a single-zone Monte-Carlo model for predicting air quality concentrations in kitchens.

1. Requirements
   1.1. Windows 7+ PC
   1.2. Microsoft Excel v2010+
   1.3. Risk Analyzer Add-In for Excel

2. Description of model files (diagram)
Running the model and generating requires three types of excel files:

2.1. **Model files** contain discrete input and outputs from the model. The most basic model predicts air pollutant concentrations on a minute-by-minute basis over the course of a day using emission rates, kitchen volumes, air exchange rates, fraction of emissions entering the room, and cooking times. More complicated models can include other factors such as background concentrations, multiple sources, exposure factors, and others. This sheet is referred to as the study file by Risk Analyzer.

2.2. **Monte Carlo Output Files** contain the predicted distributions of air pollutant concentrations generated by running the Risk Analyzer add-in. The Excel file includes a worksheet presenting the model simulation premises (descriptions of input distributions and a reference to the study file [model file]); a worksheet with all simulations values from the input variables (e.g. air exchange rates and kitchen volumes); and a worksheet with the corresponding simulation output values (mean 24 hour kitchen concentrations). Additional worksheets on that provide the sensitivity of the model to each variable can also be created.

2.3. **Post analysis templates** provide summary statistics and graphs of the output.

3. File management (opening and naming files, dropbox, etc…)
Files should be saved in the Box Model LINEB Dropbox according to the following file structure.

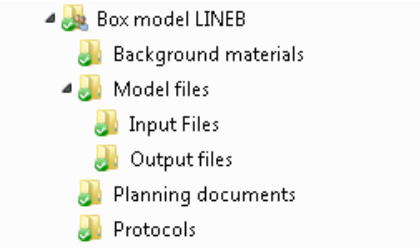

Figure A1. File Management

*Addition of subfolders in the model file folder may be appropriate for specific stages or versions of the model.

3.1. The input, or study files, will always be the same name for a given version of the model (not for each monte-carlo simulation run). File names should be "IAQ model (descriptor of model: eg basic or full) vX.xlsx. E.g "IAQ model basic v1.xlsx."

3.2. The output files must be named individually to provide an indication of the simulation premises used for the given model run. File names should be the name of input file, plus and indicator of the premises of the model run. E.g. "IAQ model basic v1_fogon wbt a.xlsx".

3.3. Users should email the group to indicate when models are being run to avoid conflicted copies of input files. When working on non-input files, file names should be appended with "_user initials_ working". When finished, remove the "_user initials_working" and update the version number.

4. Creating name ranges

4.1. Defining name ranges: It is necessary to define the parameters to be used in the box model. Two types of parameters to be used; input and output parameters. For Risk Analyzer to be able to identify these parameters, they must have a "Name" referenced to a cell in the Excel model file. In the "Formulas" tab, the "Name Manager" allows us to create or edit a "Name" and select the respective cell. This window shows all the variables that have been created, and is possible create a new, modify and delete names of variables (See Figure A2). The names can be changed as well as the location of the values. You will be unable to run the model without the name of the corresponding parameters. Note that input parameters should be a cell with a given value and the output will be a result of a formula. Names cannot start with a number or have spaces, and it is recommended that they be short so they are easy to identify.

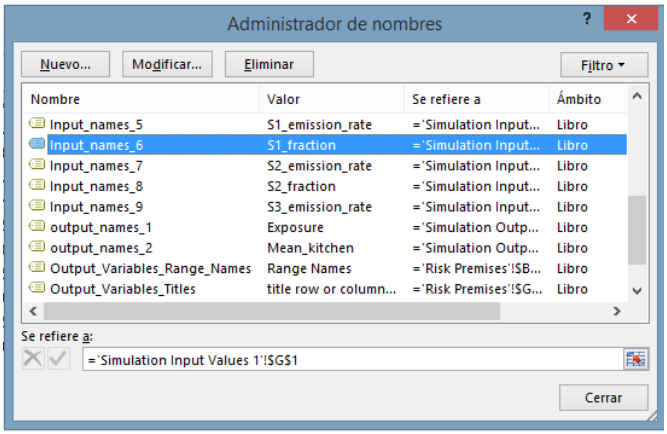

Figure A2. Name Manager Window.

5. Entering inputs

Inputs for the model are highlighted in blue in the Excel spreadsheet of the model file. These include places to enter emission rates, kitchen volumes, ventilation rates, cooking times, and the fraction of emissions entering the room. The model will update base on the inputs and provide discrete estimates of mean 24 hour concentrations.

6. Running Risk Analyzer

6.1. Creating a study file

Once the program has been installed, you can go to the "Specialty" tab and look for the "Risk Analyzer" icon, the following window is displayed. Prior to this step is necessary to have saved the file (See Figure A3).

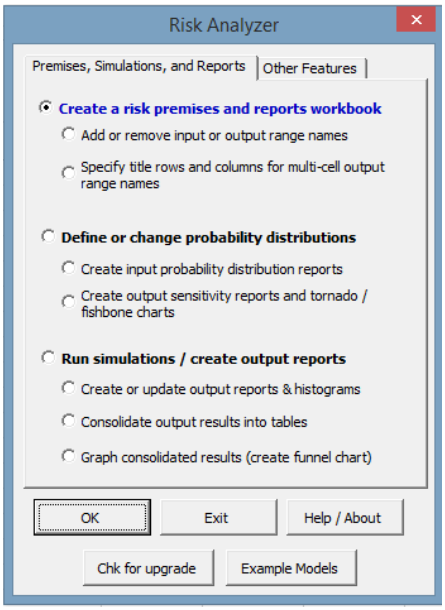

Figure A3. Create a risk premise and report workbook.

Select "Create a workbook risk premises and reports." You need to select the file of study in which we are working. This window displays currently open files. It is necessary to enter a description of the risk study (See Figure A4).

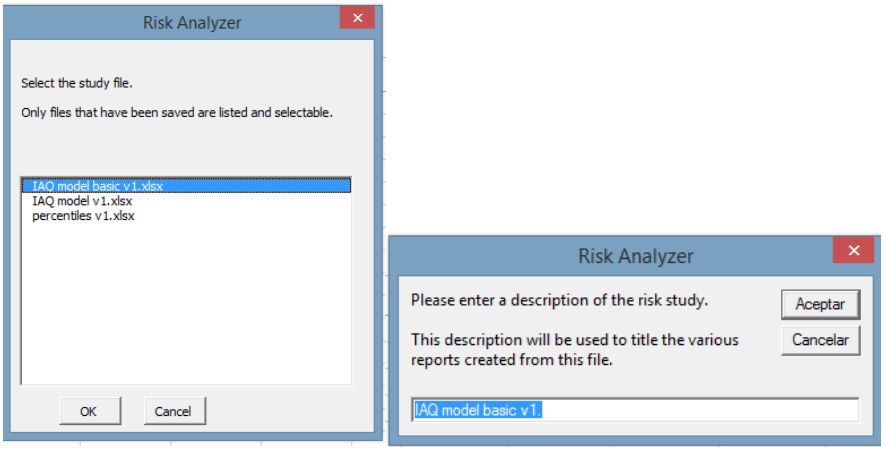

Figure A4. Selection and description of the risk study.

Now select the ranges names that identify the Output and Input cells in your model (See Figure 5). Finally the risk analysis premises and reports workbook has been created (See Figure 6).

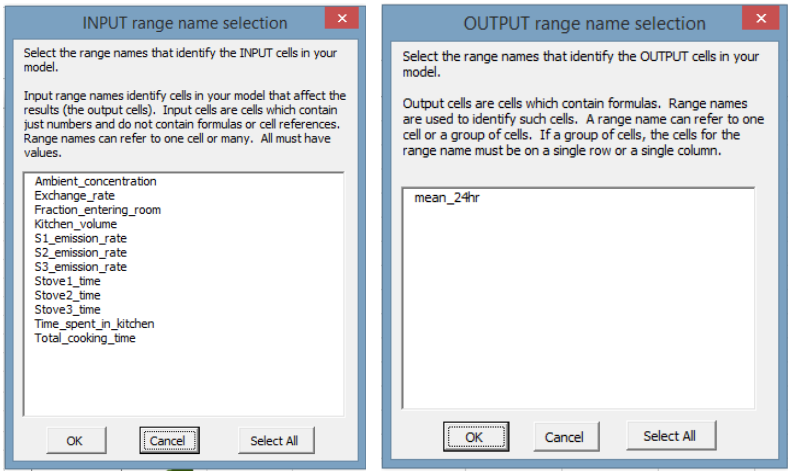

Figure A5. Outputs and Inputs of the model.

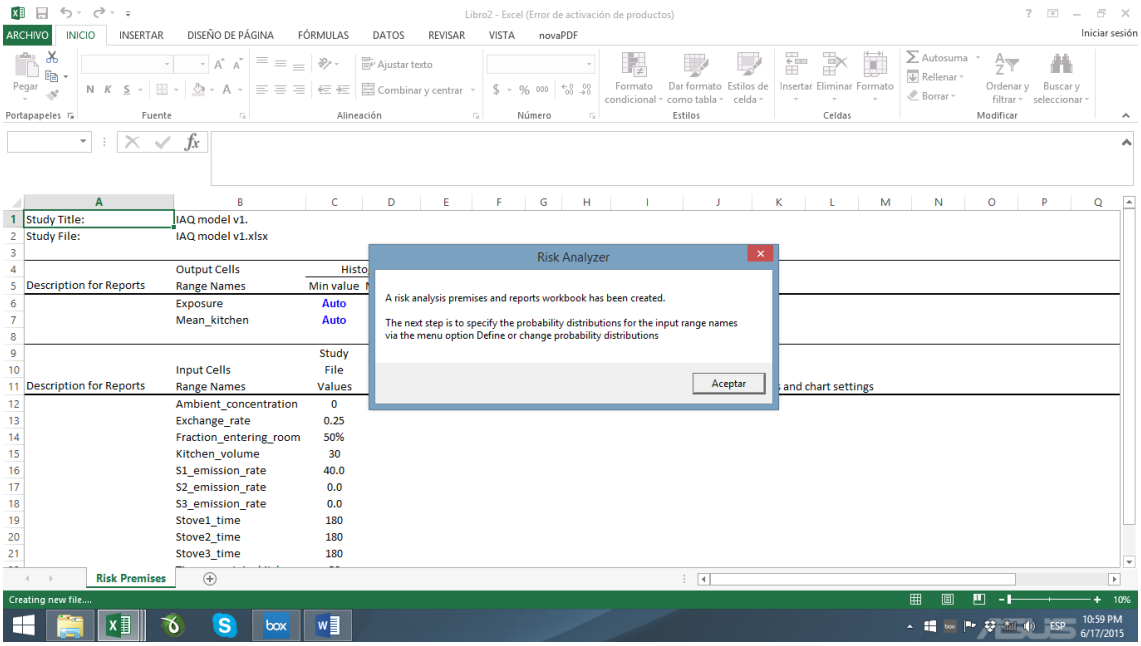

Figure A6. Risk analysis premises and reports workbook.

6.2. Selecting distributions

To define probability distribution, the first step is selecting an input range name and then selects the best distribution to use (normal, triangle, beta log-normal, uniform, exponential, Poisson, etc) (See figure A7).

You need to specify maximum and minimum value, standard deviation and average. In this window you can update the changes made to the above parameters; change distribution and accept or cancel it displayed in the window. Once you finished with the input selected and if is necessary, repeat the same procedure with the other existing inputs (See Figure A8). Note that you won't be able to enter anything other than 0 for the minimum for a lognormal distribution. This can be updated later.

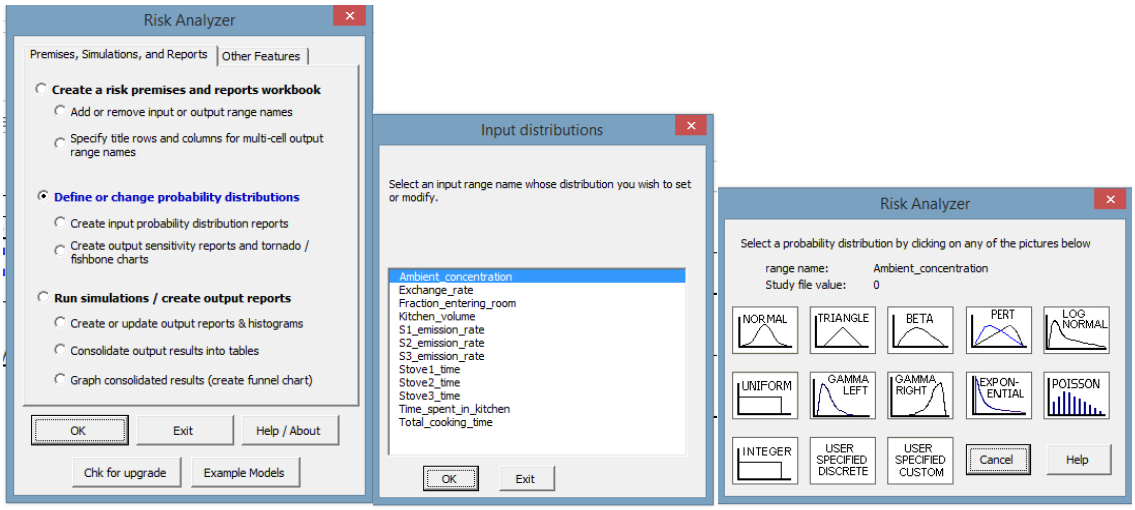

Figure A7. Selecting distributions

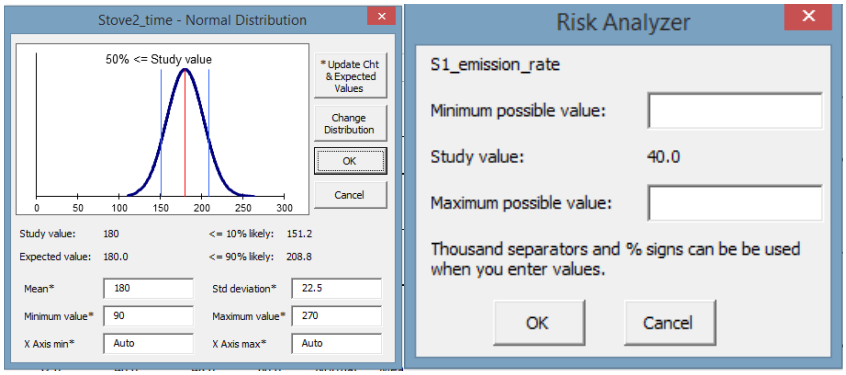

Figure A8. Minimum and maximum values for the selected distribution.

6.3. Running simulations

To run simulations you need to create a report output. Before risk analyzer realize the simulations, you must indicate the number of simulations to be performed, as well as select the input and output variables (See Figure A9). The simulation will take a few minutes depending on the number of simulations that are intended to perform (see Figure A10). Typically 5- 10,000 will be enough.

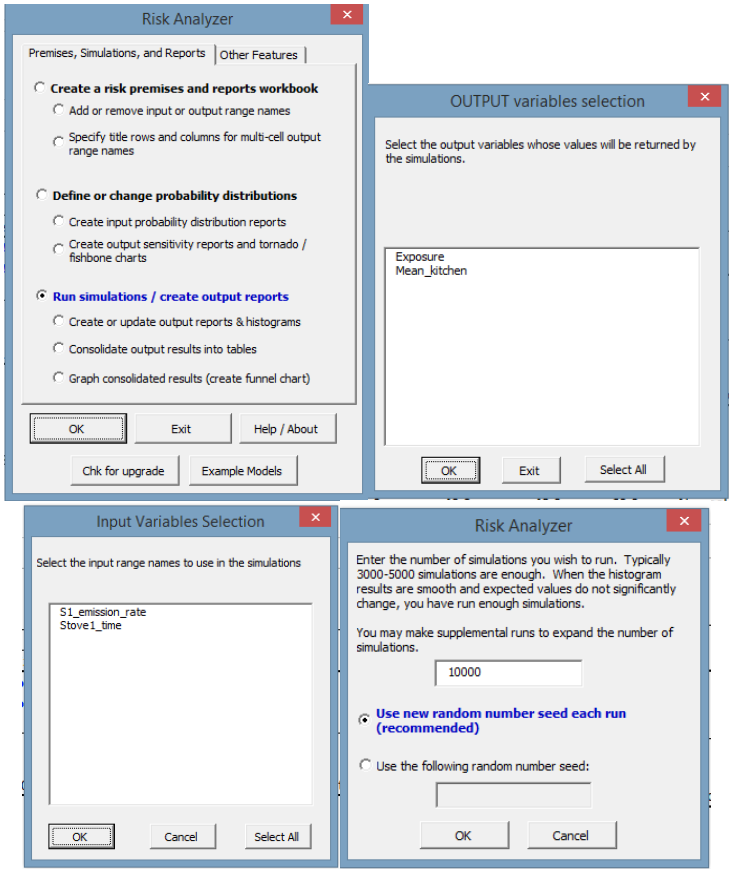

Figure A9. a- Run simulations b- Simulation to wish run, c- Input variables selection y d- Output variables selection.

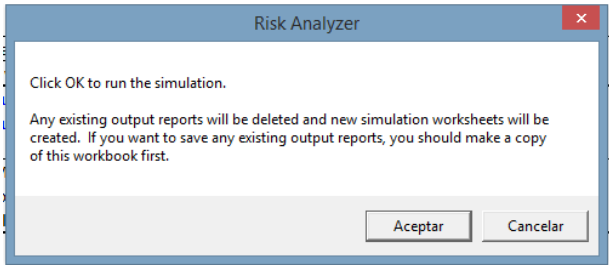

Figure A10. Run a simulation.

6.4. Ouptut reports.

Once the simulations are complete, you will be given the option to create various output reports. You may select and create any as desired. If you wish to create a sensitivity report, you must click on the Risk Analyzer icon and select the option to create an output sensitivity report. This will not require the model to run an additional simulation, but will simply generate the report as desired.

7. Post Analysis and back calculating emission rates
    a. A template for calculating summary statistics is provided to expedite analysis ("Output analysis template v1.xlsx"). The template calculates the mean, median, min, max, 10^{th} percentile and 90^{th} percentile of the output. To use the template, open the file and copy columns C-L, and paste them into the output simulation worksheet columns C-L. You can enter air concentration targets/thresholds in the blue cells and the percent of simulations meeting the target will be calculated.
    b. Graphing template. It is necessary built a histogram to express the % of simulation of the output concentrations.