World Health Organization

Model documentation: WHO Performance Target (PT) Model

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1. Introduction

The WHO Performance Target model (PT model) derives emissions targets for indoor combustion technologies used for cooking, lighting, heating and other household energy needs. The PT model calculates the emission performance for different geographies or contexts based on the observed room air change rates and volumes; the fraction of emissions from the sources that enter the room (can be important for chimney stoves); and the times the devices are used. The model is 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 PT model is intended to be used by governments or programmes that seek to establish emissions performance targets specific to their region or context, and compliments other efforts to support standards for cookstoves. For example, ISO has released a technical report, Clean cookstoves and clean cooking solutions- Harmonized laboratory test protocols – Part 3: Voluntary performance targets for cookstoves based on laboratory testing (ISO, 2018). This ISO technical report contains tiers of performance for five attributes of cookstove design: efficiency, emissions of CO, emissions of PM, safety and durability. WHO has developed implementation guidance for the national adoption of voluntary performance targets (VPTs). The PT model described here is the model that was used to develop the ISO voluntary performance targets. The primary application of the PT model is to derive **context-specific targets (or tiers)** for PM and CO emissions.

The performance targets can be used within a standards framework to guide which technologies are more or less likely to provide health benefits. Specific users of the model are anticipated to be technical groups, such as testing laboratories and organizations, which work with government ministries, standards-setting agencies, and programme implementers to inform their performance targets for cookstoves and clean cooking solutions. Aside from formal standards setting activities, the PT model can also be used to explore how changing conditions (e.g. changes in ventilation rates or cooking times) relate to stove emissions performance targets. Importantly, the model is only intended to illustrate the potential impacts from different levels of emissions and is not intended as a replacement for technology or programme evaluation in field settings.

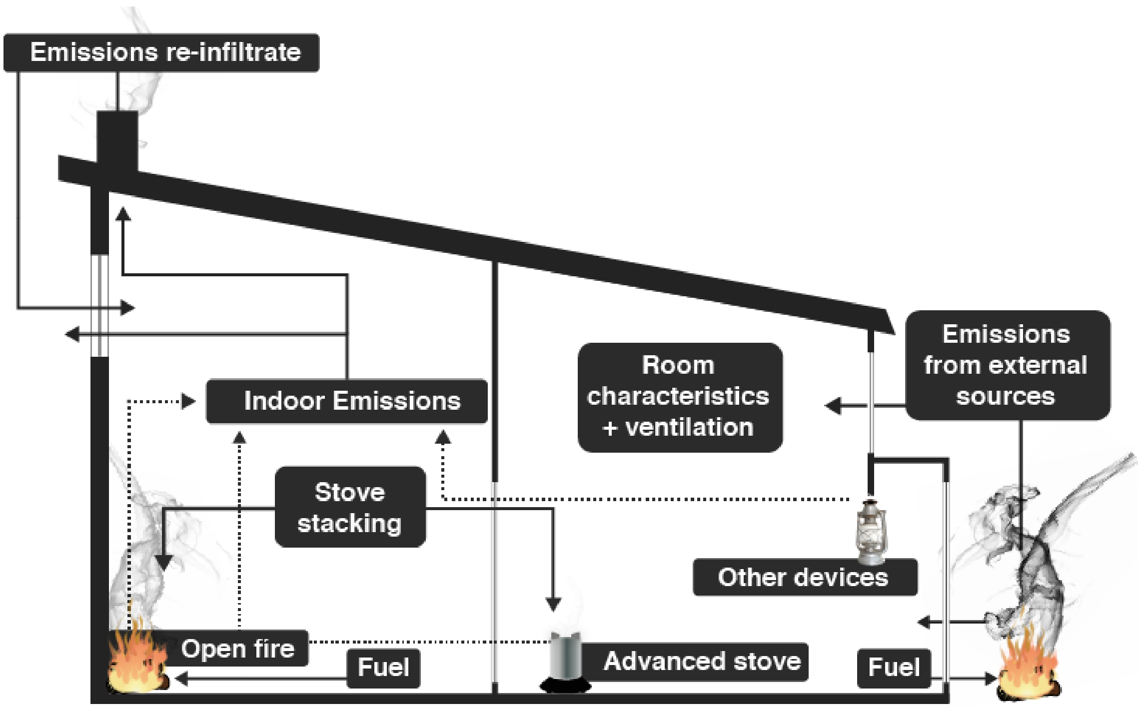
This document provides theoretical underpinnings of the model and background for its development and serves as a guide to running the web-based version.

2. PT model theory and background

The relationship between emissions sources and indoor air concentrations involves several factors, as shown in Figure 1, although emissions from stoves and other devices 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 (although the model could be used with similar devices, such as space heaters). At any given air change rate (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). These factors, however, are not included in this model as the goal is to provide constructive emissions performance guidance for single technologies, and thus this model only focusses on the emissions and associated household air pollution from a stove indoors.

For users interested in the effects of these parameters on household air pollution concentrations and personal exposures, the WHO Household Multiple Emissions Sources Model (HOMES) was developed as a complementary model. The WHO HOMES model includes inputs for multiple emissions sources, ambient concentrations, and estimates kitchen concentrations and personal exposures. While it does not provide strict guidance on emissions performance, it is useful in illustrating potential air quality and exposure scenarios for more varied, real-world scenarios. This model and corresponding documentation can be found online.



Note: figure produced by Ajay Pillarisetti, UC-Berkeley

Figure 1. Factors impacting indoor air quality

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 source is 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 (such as a fan), and this supply is matched by an outflow of room air by exfiltration and/or mechanical means at the same rate. The effect of a chimney, hood, or other venting mechanism which removes emitted pollutants before they mix into the general kitchen air, can also be accounted for by only including a fraction of the emissions rate. Contributions from the emissions sources are defined by an emission rate (the mass of pollutant emitted over a specified time), together with the duration of those emissions. Based on these parameters, the pollutant concentrations in a room can be estimated over time.

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 modeling 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 illustrate a framework for combining stove usage and performance to estimate impacts of a given programme 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 presented in Johnson et al. 2011, which was originally developed and presented based on fieldwork in India (Johnson, 2011). A simplified version of that model was then 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 from this evidence chapter reproduced below shows that the modeled distributions and measured distributions for various stove/fuel combinations overlap substantially. Although the model does appear to overestimate concentrations compared to real-world conditions, this potential bias would be conservative in the application of the model (e.g. lower emissions performance targets than those needed to meet AQGs would be estimated).

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 modeling 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 modeling 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.

PT Model Description

The PT model described here is a single zone model which applies to a single source (stove), and is the same as that presented in the WHO Guidelines for Indoor Air Quality: Household Fuel Combustion (Johnson et al., 2014; WHO 2014). The relationship used in the PT model between the various input parameters (as described above) and the room concentration of the pollutant of interest (i.e. $PM_{2.5}$ or CO) can be expressed mathematically, as follows (Equation 1):

Equation 1. $$C(t) = \frac{qf}{\alpha V}(1-e^{-\alpha t})+C_o(e^{-\alpha t}),$$

where

$C(t)$ = Concentration for a given time point
q = emission rate for source (mass of pollutant/min)
f = 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)

The model produces 24 hours of minute-by-minute concentration estimates (1440 minutes), where the emission rate for the stove is 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 active emissions periods from the stove are used for the model for computational simplicity. In practice, different spacing between emission periods –which may reflect actual use more realistically - makes little difference to the 24-hr pollutant concentration results.

To calculate the predicted 24-hour 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).

Equation 2. $C_k = \sum_{1}^{1440} \frac{C_i}{1440}$

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 modeling, 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 $PM_{2.5}$ or CO. For the PT Model, the Monte Carlo approach accounts for varying the input parameters such as kitchen volume, stove use time, and air change rate, according to the variation that has been observed for a given context or population. With the input information varied according to the population of households being considered, the outputs (e.g. kitchen concentrations) are then described as distributions. Figure 3 illustrates this approach, in which 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 and duration, and outputs the distribution of estimated pollution levels in a hypothetical population of households. Applying a Monte Carlo approach to the PT model provides results which are specifically tailored to the unique distributions of kitchen volumes, cooking times, and air change rates for a given context.

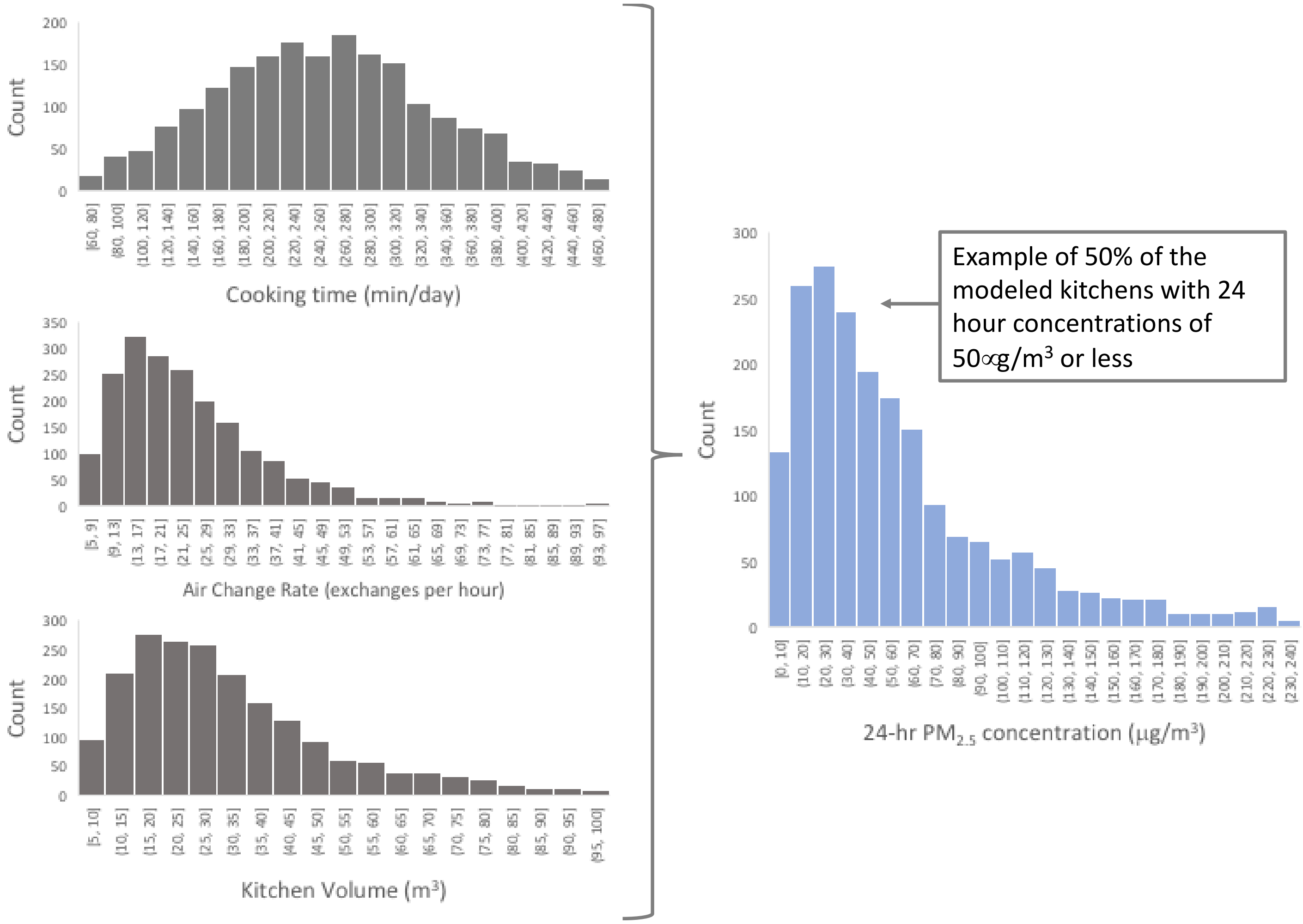


Figure 3. Illustrative input distributions (left) are used to iteratively select values for the model, which then produces a distribution of predicted kitchen pollutant concentrations (right). The right-hand graph shows an example of a fraction of modeled kitchens meeting an air quality target (in this case 50µg/m^3) given the assumed input distributions on the left of kitchen volumes, air change rates, and cooking times.

Linking emissions performance with health protection

The model's output distribution can then be compared to the WHO air quality guidelines to determine what level of protection the inputted emissions rate is estimated to provide. To derive which emissions performance levels are associated with predetermined levels of health protection, the Monte Carlo approach is repeated with different emission rates until the desired levels of protection are achieved[1]. Figure 3 illustrates this process, with the distribution of output concentrations presented on the right, indicating the potential fraction of the population which would meet a given air quality guideline on the x-axis. In this specific case, the emission rate of

[1] The PT model runs 250 Monte Carlo simulations for each 0.01 emission rate increments from 0=1 mg/min, and 0.1 increments from 1-100 mg/min for $PM_{2.5}$; and for each 1 mg/min increment from 1-1500 mg/min for CO.

2.7mg/min of $PM_{2.5}$ combined with the input distributions for cooking time, air change rate and kitchen volume resulted in 50% of modelled kitchens being at or below 50μg/m^3, which is equivalent to PM emissions Tier 4 in the ISO voluntary performance targets. For other ventilation and kitchen size scenarios, the output distributions would differ and therefore the emission rates guidance would differ as well.

3. Running the PT model

Guidance related to programmatic implementation of the model is provided online. That guidance is designed to give context about how this model fits within a programme or government standards framework. Here, specific step-by-step instructions are provided on how to run the model.

Entering input parameters

The PT model is available to use online. To run the 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 online.

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.
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*.

Step-by-step instructions for entering the inputs are provided here with an example screenshot provided in Figure 4:

1. Navigate to the inputs page by selecting the "Inputs" tab on the left-hand menu.
2. Select the pollutant of interest from the dropdown menu (PM or CO).

3. Enter the distributional statistics for cooking time, the fraction of emission which enter and mix in the room, air change rate, and kitchen volume.
4. Select the shape of the input distribution in the pulldown menus. Note that the default selections are based on what has been observed in previous data and it is only recommended to change the input distribution shape if there is available data which suggests a different distribution for the specific context being modeled.
5. Once all of the inputs are entered, select the "Run the Model" tab from the navigation bar on the left to start the Monte Carlo simulation. Note that it will take a few minutes for the model to run as it will be doing 275,000 iterations for $PM_{2.5}$ or 375,000 for CO.

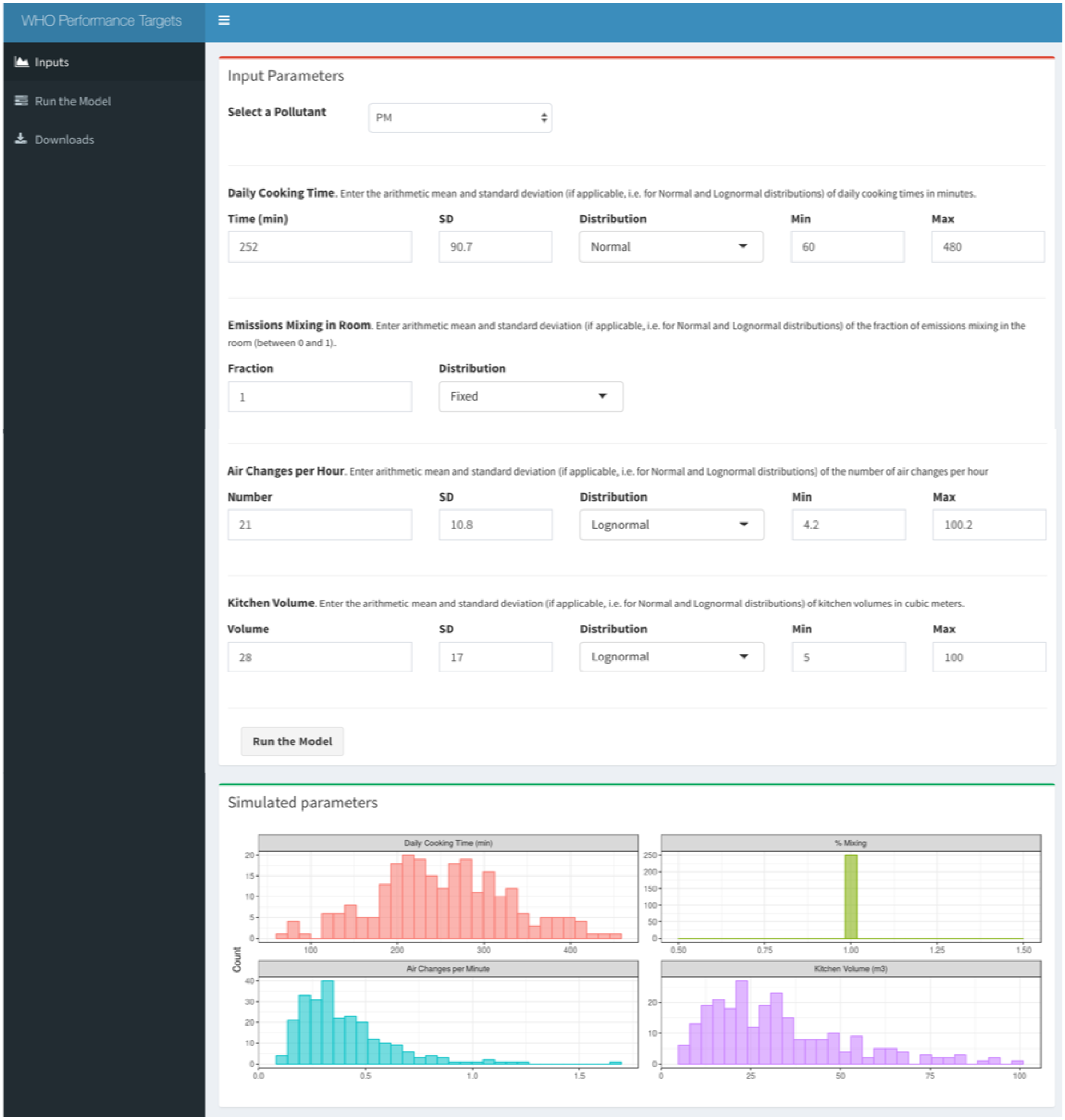


Figure 4. Example of the inputs for the PT model. The user enters input parameter statistics and selects the appropriate shape of the distributions. In the bottom of the screen, example distributions of these inputs as generated by the Monte Carlo simulation are shown.

Model outputs

Once the model has completed running, the output page will then show the estimated emission rate performance values (given the set of inputs entered) required to reach the air quality targets (and associated relative risk) for the ISO tiers of performance. As shown in Figure 5, tiers of performance (from 1-5) are presented along with the associated emissions rates and emission factors to meet the given target. The tiers shown here align with those in the ISO voluntary performance targets (ISO 2018). Note that the “coverage” column represents the percent of homes that meet the given air quality or relative risk target.

For $PM_{2.5}$, there is a box that shows the “level of protection”, or the acute lower respiratory relative risk associated with chronic exposure to that concentration. The user can select from the five Tier values shown, or type in their own value into the box, which will change the summary table at the top and the “fraction of households protected at various emission rates” graph to include the “User Input” value entered by the user. In Figure 5, for example, a concentration of 10 $\mu g/m^3$ has been entered as the user-selected threshold. The graph and tables reflect the emission rates that would be required for 50% of homes to be at or below 10 $\mu g/m^3$.

Similarly, the CO targets are aligned with different levels of protection (coverage) as measured by the estimated percentages of homes with estimated CO concentrations below the 24-hour WHO guideline for CO of 7 mg/m^3 (WHO 2010). The rationale and explanation for alignment with these health risks, as well as background information on these health impacts, is provided in WHO’s guidance document on standards implementation, available online.

The coverage column represents the percentage of modeled homes that would have concentrations at or below the target level. Additional graphs are provided showing the percentage of homes meeting a given target across different emission rates, as well as the distribution of concentrations for the user input concentration.

Users can select a “level of protection” (as a 24 hour mean concentration) for CO from the preselected values in the dropdown menu which align with the ISO VPT tiers, or enter a different value directly as text in the “level of protection” window on the “Run the Model” tab.

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.

WHO Performance Targets

- Inputs
- Run the Model
- Downloads

Households Meeting Targets

Tier	Emission Rate (mg/min)	Coverage	Emission Factor (mg/MJd)	Pollutant
User Input (10 µg/m3)	0.6	50%	13.7	PM
Tier 5 - RR 1 (10 µg/m3)	0.22	90%	5	PM
Tier 4 - RR 1.5 (50 µg/m3)	3	50%	68.7	PM
Tier 3 - RR 2.5 (170 µg/m3)	10.2	50%	233.7	PM
Tier 2 - RR 3 (400 µg/m3)	24	50%	549.8	PM
Tier 1 - RR 3.15 (800 µg/m3)	48.1	50%	1101.9	PM

Showing 1 to 6 of 6 entries

Coverage is the percent of modelled homes meeting the tier level. Please note that emission targets will vary slightly if you run the model multiple times, even when using the same input parameters. This variation occurs because the inputs for each of the thousands of simulations are randomly drawn from distributions based on your inputs. It is recommended that targets from the first model run from any given set of input distributions be used.

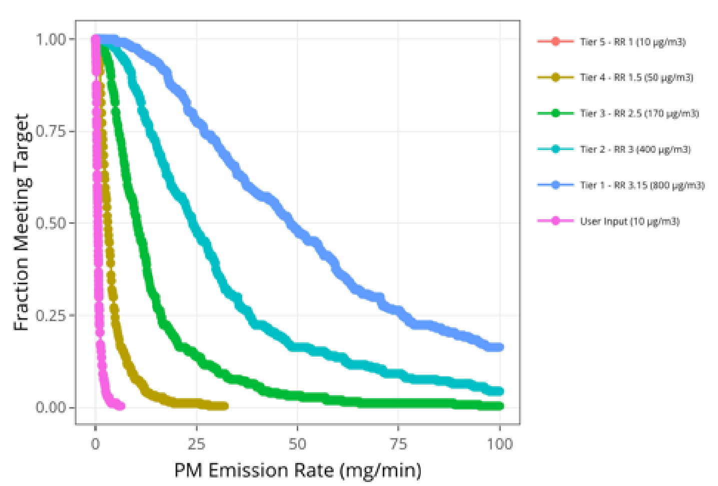
Levels of Protection

Level of Protection. Users may enter a concentration target in µg/m^3. For example, these can be from local or national air quality guidelines. The summary table above and the graph below will change to reflect any user input concentration. As long as input concentrations are the same, it is not necessary to re-run the model, and multiple different concentration targets can be entered.

Tier 5 - RR 1 (10 µg/m3)

Summary. To protect 50% of households at a 24 hour average PM concentration of 10 µg/m^3, the maximum emission rate should be 0.6 mg/min or lower.

Fraction of households protected at various emission rates



Distributions of 24-hour concentrations for user selected target

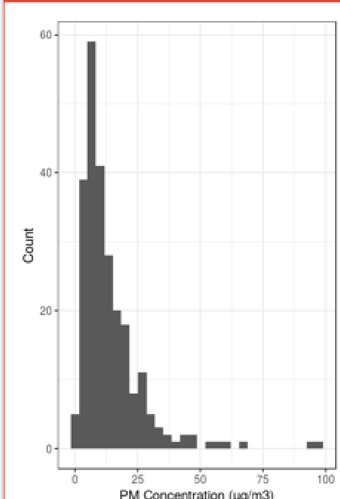


Figure 5. Example output showing the estimated performance targets for tiers of performance corresponding to the ISO Technical Report 19867-3:2018, Clean Cookstoves and clean cooking solutions – Harmonized laboratory test protocols – Part 3: Voluntary performance targets for cookstoves based on laboratory testing (ISO 2018).

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Please contact householdenergy@who.int with any questions.

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