Refining the particulate matter airway deposition arising from indoor cooking-related biomass combustion for children in the Haramaya district in Ethiopia

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Abstract

Background: Air pollution, a global issue affecting millions of individuals, is linked to adverse health effects on the respiratory system, but also to e.g., cancer and cardiovascular ailments. In low-income countries, cooking is often conducted by biomass-combustion, causing women and children to be exposed to high levels of indoor air pollution. **Method:** A mathematical model has been developed in MATLAB to estimate the mass of particulate matter deposited in the respiratory tract, to study correlations between lung deposition of indoor air pollution and respiratory symptoms of children aged less than 5 years old in a cohort of Ethiopian individuals (using STATA), with the input variables time spent cooking and fuel type usage (in this case, wood, charcoal, and animal dung). **Result:** The model was able to portray a higher estimated deposition for individuals using more polluting biomass practices, where cow dung had the highest estimated deposited particulate matter mass and deposited particle number, while charcoal had the lowest, showing statistical significance. A statistically significant decrease in risk for respiratory symptoms were noticed for the children for higher mass deposition values, with an Odds ratio (OR) of < 1 for both the entire and alveolar respiratory tract. The result remained valid in multivariate analysis with similar OR and p-value, where a statistically significant confounder being smokers in the household as well as usage of animal dung as fuel compared to wood, both with an $OR > 1$, p-value < 0.05. **Conclusion:** The model presented in this report can produce mass and number estimates for particulate matter deposition, enabling estimates using few input variables, allowing for new analysis methods in low-income settings, showing differences in estimates depending on fuel type usage. However, it needs further development, likely focused on identifying more confounders, but also more in-data in the form of size distributions from more combustion events.

Keywords: Air pollution exposure, charcoal, wood, animal dung, low-income setting epidemiology

Sammanfattning

Bakgrund: Luftföroreningar är ett globalt hälsohot som bland annat påverkar luftvägarna och hjärt-kärlsystemet hos miljontals individer årligen. I låginkomstländer bedrivs ofta matlagning genom förbränning av biomassa, en process som skapar höga halter av luftförorenande partiklar, vilket i sin tur utsätter hushållets medlemmar för hälsorisker. **Metod:** En matematisk modell som estimerar den massa av luftföroreningspartiklar som deponeras i luftvägarna, har utvecklats för att uppnå en tydligare uppskattning av exponering, baserat på matlagningstid och bränsletyp. Modellen prövas även genom att genomföra statistisk analys mellan den estimerade massan luftvägspartiklar och luftvägssymtom hos barn under 5 års ålder i en studiepopulation i Haramaya-provinsen i Etiopien. Modellen är utarbetad i MATLAB och STATA har använts för datahantering och statistisk analys. **Resultat:** Modellen kunde statistiskt signifikant skilja den estimerade massdeponeringen tillika partikelantaldeponering i luftvägarna åt, då studiepopulationen delats upp baserat på vilken bränsletyp som används, där djurdynga hade högst estimerad mass och antalsdeponering medan kol hade lägst. Ingen statistisk signifikant ökad risk för luftvägssymtom med ökad massdeponering. Resultatet kvarstod i multivariatanalys, där statistiskt signifikanta confounders visade sig vara rökare i hushållet. Det noterades även att när djurdynga användes i stället för trä, ökade risken för luftvägssymtom. **Slutsats:** Modellen som utvecklats kan differentiera mellan använda bränsletyper, både gällande uppskattningar av massa och partikelantal, samtidigt som den behöver få variabler, vilket möjliggör analys i mer låginkomstmiljöer. Modellen behöver förvisso vidareutvecklas, förmodligen genom att identifiera fler confounders, samt genom mer replikat av förbränningsexperiment och deras subsekventa storleksdistributionsdata.

Nyckelord: Luftföroreningsexponering, kol, ved, djurdynga, låginkomstfokuserad epidemiologi

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Lund, May 2023

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Abbreviations

AER: Air Exchange rate

ANOVA: Analysis of Variance

BC: Black carbon

CI: Confidence interval

CO: Carbon monoxide

DF: Deposition fraction

EPA: Environmental Protection Agency

HDSS: Health and demographic surveillance system

HHV: Higher heating value

IAP: Indoor air pollution

IAQ: Indoor air quality

IARC: International Agency for Research on Cancer

ICRP: International Commission on Radiological Protection

IEA: International Energy Agency

IF: Inhaled Fraction

LHV: Lower heating value

LIC: Low-income country

LTH: Faculty of Engineering at Lund University

NO: Nitric Oxide

OR: Odds Ratio

PAH: Polyaromatic Hydrocarbons

PM: Particulate matter

SD: Standard deviation

SMPS: Scanning Mobility Particle Sizer

WHO: World Health Organisation

1. Background

This master's thesis work was performed at the Division of Ergonomics and Aerosol Technology, Department of Design Sciences, Faculty of Engineering (LTH), Lund University, Sweden, in collaboration with research associates at Haramaya University College of Health and Medical sciences, Ethiopia.

1.1 Global perspective

The Textbook of International Health (1) describes pollution as "substances in the environment detrimental to the quality of human or other life" (page 281) and describes air pollution as a major hazard. Air pollution, or rather airborne particulate matter (PM) includes several different components and can be classified according to their particle size, more precisely, their aerodynamic diameter, meaning the assumed spherical space that is representative of the PM, with a defined unit density (2). Furthermore, PM is often defined in size ranges of aerodynamic diameter, such as PM10 (PM with an aerodynamic diameter < 10 µm) and PM2.5 (PM with an aerodynamic diameter < 2.5 µm) (3). The health guidelines provided by the World Health Organisation (WHO) for PM exposure are set at PM2.5 annual average and 24-hour average exposure of 5 $\mu g/m^3$ and 15 $\mu g/m^3$, respectively (4, 5). Guidelines has also been described for PM10 for annual average and 24-hour average exposure of 15 $\mu g/m^3$ and 45 $\mu g/m^3$, respectively (4, 5).

According to the WHO, 6.7 million deaths annually are caused by outdoor (also called ambient) and indoor air pollution (IAP; responsible for 3.2 million deaths) (6, 7). At this moment, 99 % of the global population is living in areas where the levels of pollution are above the WHO guidelines of annual mean exposure(6, 7). Air pollution is responsible for a diverse range of health-related ailments, both transient and chronical complications arising suddenly or after prolonged exposure (8). Bruce et al (9) showed the diversity in ailments that can affect individuals exposed to air pollution, highlighting infections, malignancies (where several different types (10) has been seen, e.g., lung (11) and (12) breast cancer), other respiratory syndromes, and cataract. Several studies have seen associations with adverse cardiovascular events, such as atherosclerosis and stroke (13-15). Furthermore, associations with altered birth outcomes such as pre-term birth weight, small for gestational age births, and preterm births has also been shown (16-18).

Around 50 % of the world's population rely on combustion of solid biofuels such as charcoal and wood to provide household energy, with an increased dependence observed in rural communities in low-income countries (LIC) where up to 90 % rely on this (9). In fact, approximately 2.6 billion individuals use solid carbon-based fuels on simple stoves in their households (19) and IAP in LICs is mainly derived from solid biofuel combustion used for cooking, lighting, or heating (20). In most LICs, cooking is conducted indoor by women, also when pregnant, often without ventilation opportunities that would shield her and the household members, resulting in a poor indoor air quality (IAQ), which is an urgent problem that so far has received too little attention (20, 21). Furthermore, the International Agency for Research on Cancer (IARC) has described the carcinogenicity, i.e., a term describing the associated risk of causing cancer, of household practices (22). Here, the IARC classified combustion of biomass as a group 2.A carcinogenic, indicating that this practice is probably carcinogenic to humans, while combustion of coal has been classified as a group 1 carcinogenic, indicating that this practice is deemed as carcinogenic to humans. Additional recommendations regarding stove-related air pollution has since been provided by the WHO (23), implementations and reforms to prevent usage of simple stoves relying on combustion of solid fuels has, however, not

successfully reduced the number of individuals exposed (24). Certain studies regarding IAP in LICs has been lacking important details, such as combustion material or type of stove used (25), while other studies regarding exposure to PM in LICs has found a correlation tendency with the health outcome of interest (in this case adverse pregnancy outcomes) and PM exposure (26). Some studies have shown exposure to air pollutants at levels above WHO guidelines when conducting regular household activities, e.g., coffeemaking(27). Furthermore, IAP exposure being associated with acute lower respiratory tract infections, chronic obstructive pulmonary disease, and ischaemic heart disease (28). Regarding IAP arising from combustion of biofuels specifically, Hosgood et al (29) found correlations between individuals predominately using wood/coal as fuel, and an increased risk of developing lung cancer, where other studies (30) have indicated that usage of wood combustion heaters may affect human health by altering of the immune defence of the respiratory tract.

Assessing IAP exposure for individuals in a cohort is a more complex task than assessing ambient air pollution exposure, and in epidemiological studies the indoor exposure is therefore often simply omitted. Additionally, unlike ambient air pollution, IAP usually requires on-site measurements while ambient air pollution can be estimated using satellites, where average ambient air pollution concentrations can be measured over a given area. Furthermore, ventilation opportunities may also influence the IAP, both when preventing ambient pollution from entering the household, and for an opportunity to ventilate and thus reducing the IAP by e.g., opening windows (8).

1.2 Air pollution deposition models and equations

When it comes to estimating the deposited dose of air pollution particles in the humane respiratory tract, a model has been presented by Hussein et al (31, 32), see Equation 1. Deposited dose (Dep) is defined as

$$\mathrm{Dep} = \int_{t1}^{t2} \int_{D_{p1}}^{D_{p2}} V \cdot DF \cdot n_N^0 \cdot f \cdot d\log(D_p) \cdot dt \qquad (1)$$

where t is the time duration of the exposure; D_p is the particle diameter; V is the inhaled volume per minute; DF is the deposition fraction in the respiratory tract; n_N^0 is the lognormal particle number size distribution; f is the dose metric defining the air pollution particles, e.g., the particle surface area, e.g., $D_p{}^2 \cdot \pi$ (assuming spherical particles). By removing f, the deposition will be describing the number of particles deposited instead of the deposited surface area.

Worth noting is that the parameters DF, f, and n_N^0 are all in part defined by the air pollution particle diameter. For f, the surface area formula is defined above. The variable n_N^0 shows the measured particle number concentration for the midpoint diameter of the air pollution particles. Deposition fraction, DF, has been described in several models, e.g., the ICRP model (33), see Equation 2-4. The ICRP DF equation describes the total deposition of PM in the entire respiratory tract as

$$DF = IF\left(0.0587 + \frac{0.911}{1 + e^{4.77 + 1.485\ \ln D_p}} + \frac{0.943}{1 + e^{0.0508 - 2.58\ \ln D_p}}\right) \qquad (2)$$

where D_p is the particle diameter and inhaled fraction (IF) is described by D_p for an inhalation velocity of less than 10 m/s, see Equation 3

$$IF = 1 - 0.5\left(1 - \frac{1}{1 + 0.00076{D_p}^{2.8}}\right) \qquad (3)$$

The ICRP model can also be used for estimation of deposition fractions in, e.g., the alveolar region (33) (Equation 4)

$$DF_{alv} = \frac{0.0155}{D_p} \cdot \left(e^{-0.416\left(\ln(D_p) + 2.84\right)^2} + 19.11e^{-0.482\left(\ln(D_p) - 1.362\right)^2}\right) \qquad (4)$$

Where DF_{alv} is the deposition fraction in the alveolar section of the respiratory tract.

1.3 PM and combustion products

For complete combustion of an organic compound consisting only of carbon, each carbon atom will combine with an equal number of oxygen gas molecules, thus forming carbon dioxide, see Equation 5 (34).

$$C(s) + O_2(g) \rightarrow CO_2(g) \qquad (5)$$

In real settings, it is however not likely to find fuel consisting of purely carbon atoms. Wood, for example, has a complex chemical make-up and will thus, when combusted, generate other compounds as well. Furthermore, it is unlikely to achieve a complete combustion process, where oxygen is available to the extent required. A deficit of oxygen will generate carbon monoxide, CO (35). Another common pollutant from the combustion of solid-carbon fuels is black carbon (BC), in other words, soot, and measuring the amount of BC levels before and after an PM mitigating attempt is often a way to assess the degree of success in mitigating combustion-related pollution (36). Soot and char formation is dependent on factors such as temperature of the combustion (37, 38) and the formation of soot is a complex procedure, where the terminology of soot formation has been reviewed by Michelsen et al (39). Soot formation is a continuous process in which a conversion from gas-phase hydrocarbons to carbonised aggregated particles occurs. It is difficult to separate the different steps of the formation, as they may overlap, Michelsen et al suggests the following terminology: inception (transition from soot precursors, i.e., gas-phase hydrocarbons, to condensed-phase particles); fine structure evolution growth (partial carbonisation in combination with growth due to coagulation and gas-to-particle conversion); agglomeration (the resulting quasi-particles adhere to one another, forming agglomerates); aggregation (solid carbonised particles, with strong, branched bonds). In physical aspects, Michelsen et al describes that the soot constituents grow from approximately 1 nm to 100 nm in size, which is supported by findings from combustion experiments conducted at > 1,000 degrees Celsius with volatile residence times of 2 seconds from Wang et al (40). Other health

hazardous constituents of combustion-generated PM are e.g., polycyclic aromatic hydrocarbons (PAH), which are precursors to soot, and various metals (3), of which many have been linked to various health-related complications (41, 42).

How a biomass fuel is burnt will also affect the particle density. Dattamudi et al (43) found that burning a sugar cane standing or from the ground affected the mass concentration and particle density, with the particle density of standing burn and ground burn being 0.52 g/cm^3 and 1.12 g/cm^3, respectively. Kantová et al (44) describes a broad span of densities of aerosols from wood and coal of 1400-2000 kg/m^3 and 1300-1700 kg/m^3, respectively. Different biomass fuels have different energy density, i.e. the released energy from a given mass/volume. As a rule, the cheaper the fuel, the lower the energy density. Higher heating value (45) (HHV), the amount of energy released per combusted mass, is used to parametrise fuel energy density. Lower heating value, LHV; is analogous but does not include the latent energy of the produced water vapour, giving a lower value. Dry wood shows less energy density than charcoal, with 16.2 MJ/kg as HHV for wood compared to 29.6 MJ/kg as HHV for charcoal (46). Worth noting, both of these fuels have, in turn, lower values than more high-energy fuels e.g., kerosene and diesel fuel, showing 46.2 MJ/kg and 45.6 MJ/kg for HHV, respectively (46).

1.4 PM lung deposition and clearance

An adult human inhales on average 10,000 litres of air per day (47). The volume of a regular breath is usually defined by the tidal volume which, for an adult, is approximately 500 millilitres (48). For a paediatric population, the minute volume varies depending on age and activity level (49). The airway tract branches out from the trachea, to the few bronchi, to thousands of bronchioles, to millions of alveoli. The trachea, bronchi, and the initial part of the bronchioles, make up the conducting zone, which has the task of transporting air to the respiratory zone (consisting of the later parts of bronchioles and the alveoli) where the oxygen uptake occurs. The alveoli are small sacs surrounded by capillaries, with a thin layer (approximately 0.2 µm) of interstitial tissue separating the capillaries from the airway (48). In the respiratory zone, there are two main types of cells. Type I cells are squamous epithelial cells (i.e., a single overlapping layer of cells), typically lining the airway tract at this level with a single-cell thickness and are encompassed by a structurally supportive surrounding membrane. These airway walls form, together with the capillary cells (capillaries being the thin blood vessels allowing the oxygen uptake in the lung), the respiratory membrane, a key structure for the human body's respiration. The second type of respiratory zone cells are the type II cells. Being cuboidal in shape, they secrete a mucus containing surfactant, made up of different lipids and proteins) that reduces the surface tension of the lungs, maintaining the respiratory zone's structure. The immune system is also present in the shape of macrophages, which migrate throughout the alveoli (50). During inhalation, air passes through several anatomical structures that all have different structural and physiological functions, see Figure 1, where a complex interplay in biological structures ensure inhalation and exhalation (50). PM can deposit throughout this path and where the deposition occurs depend on the aerodynamic particle size distribution of the aerosol, described by e.g., the International Commission on Radiological Protection (ICRP) (33, 51-53). Generally speaking, a smaller aerodynamic diameter of the particle results in a deeper deposition location in the respiratory tract (54). Studies have found that particles of around 20 nm have the highest deposition probability in the alveoli (55). Three major mechanisms cause aerosol deposition (51, 54): gravitational sedimentation (the mechanism of particles depositing on surfaces as an effect of gravity); inertial impaction (deposition due to particle inertia when air flows change direction); Brownian diffusion (the stochastic movement caused by collisions with other particles and gas molecules). For aerodynamic diameters larger than 0.1 µm, sedimentation and impaction effects are more prominent,

while for smaller diameters, Brownian diffusion has a larger impact on the deposition tendencies. Darquenne (54) describes further effects that can affect deposition. The first is the effect of turbulent mixing which is when a non-laminar flow causes a mixing to occur mainly in the upper respiratory tract. Secondly, interception is the effect where particles adhere to respiratory tract walls while still following the general air flow, which is mainly seen for irregularly shaped particles. Thirdly, electrostatic precipitation can also affect deposition, where charged particles induce an attractive force by inducing charges on the corresponding cell wall. The deposited aerosols may persist with varying results in the body (33, 53). The deposited PM may be affected by the environment and thereby alter their state by e.g., dissolution and subsequent inclusion with body fluids, and phagocytosis of immune cells. The PM may also be transported by adhering to the mucus lining the respiratory tract. By adhering to the mucus, the PM may be transported through ciliary movements of the epithelial cells to the mouth, where they consequently can be swallowed to the gastrointestinal tract. Particles can also remain in the alveolar tract and accumulate there.

Although evidence is gathering regarding the IAP effects on human health, there is still a lack of studies regarding IAP exposure in LIC settings, which is a health concern that urgently needs to be addressed. Health effects of different household activities that involve practices with known correlations to different diseases and syndromes have not been properly investigated, mainly due to lack of exposure data, and further exposure assessment tools are needed in order to investigate the effects of cooking-related biomass-combustion.

1.5 Objective

This study intends to create a model estimating IAP exposure, more precisely the deposited mass and particle number of PM in the respiratory tract, depending on fuel type and usage, to unlock new investigative opportunities. The main objective with this study is to develop a model that with limited input variables (in this case, time spent cooking and fuel type usage), can estimate the lung deposited mass of PM arising from biomass-combustion related to household cooking activities. The experimental in-data for the model is based on studies of combustion experiments in Lund, Sweden. To test the model, the thesis includes an initial statistical analysis investigating differences in estimated deposited mass depending on fuel type usage, as well as using the subset of health effects in a cohort of the households of the Haramaya district of Ethiopia.

1.6 Study Aims

1. Develop a model that requires only the limited amount of input variables normally available in LIC studies, to estimate the deposited mass in the respiratory tract arising from cooking-related biomass combustion exposure.
2. Describe a generalisable approach to use the model for different demographics, allowing for analysis of different demographic groups.
3. Use the model to estimate the deposited mass of PM in a subset of the cohort population of the Haramaya district in Ethiopia.
4. Investigate if noticeable differences between fuel type usage groups can be seen in the resulting estimated mass deposition from the model.

5. Conduct an initial test of the model by investigating potential associations between adverse health outcomes and the estimated deposited dose.

1.7 Study Questions

1. Can the aerosol deposition models found in literature be adapted to describe the deposited mass of PM arising from biomass combustion for IAP estimation in LICs?
2. What findings are seen when implementing the model, developed by combining in-lab combustion experiments of PM (using ventilation details from on-site in-house measurements) with a cohort population, practicing the combustion activities of interest?
3. Are the findings from implementing the model in-line with the previous findings in the area and can differences in mass deposition be seen in the population?
4. Can the developed model show a difference between deposited mass of PM from cooking activities using biomass-combustion depending on fuel type usage?
5. Is there a correlation between deposited mass of PM from cooking activities using biomass-combustion and adverse health effects of residents of the study population?

2. Ethical Considerations

An application to the Ethical Review Authority of Sweden, describing the intended use of collected personal data from the Haramaya Health and Demographic Surveillance System study cohort in Ethiopia, which has been approved and accepted, has been performed within this thesis work. Ethical approval has previously been granted from Ethiopian authorities regarding the study cohort.

The student has ahead of ethical approval devised a model estimating indoor air pollution mass deposition for indoor household cooking-related biomass-combustion activities not requiring any personal identifiable data. When ethical approval was granted by the Ethical Review Authority of Sweden and demographic/health data was received, the cohort details regarding anonymous details, i.e., time spent cooking per day and fuel type usage, was used as in-data. The demographic data and health data was received pseudo-anonymised, minimising the risk of intrusion of any private information, and was later used to investigate possible correlations with the developed model. The location of the households was anonymised where only the grouping of housing districts and housing number (with anonymised names and numbers) was seen. Likewise, personal identification numbers and other identificatory details were replaced with anonymous ID numbers. Additionally, the health outcomes were not described any further than whether individuals of a certain age span had experienced certain symptoms, leaving out diagnoses and specific dates of symptom presentation, allowing for anonymity in health ailments. Further household details were assessed in the cohort data. The cohort data was saved on an external hard drive before data management and was later analysed on the same computer, minimising risk of data transfer and misplacement of data.

3. Study Relevance and Benefits

This study develops a novel approach, which could provide more accurate exposure models regarding individuals in LICs and other situations, by assessing the deposited dose of, cooking-related biomass-combustion air pollution. Presently, the polluting aspects of combustion practices are well-known, as well as the broader impacts of exposure to air pollution. However, the exposure and subsequent health effects to individuals in LICs by combustion-related household practices has not been sufficiently investigated, resulting in a lack of knowledge regarding a health risk for these individuals. By applying statistical analysis, investigating correlations with the model being developed and health outcomes of interest, associations may be found that would contribute to the current knowledge regarding both this group's PM exposure and with its associated health effects, hence providing more information on the associations between individuals in vulnerable settings and air pollution.

4. Materials and Methods

A model was developed to assess the deposited mass arising from exposure to cooking-related biomass combustion in the respiratory tract (both as a whole and for the alveolar region). By using Scanning Mobility Particle Sizer (SMPS)-derived lognormal distributions from combustion experiments to be able to create a mass size distribution curve reference for each used fuel type, while including fuel type usage and time spent cooking per day as input data for estimating the deposition for each household member, the model will estimate the deposited mass of pollutant in the respiratory tract. The model is based on a mathematical model further developed from the model described by Hussein et al (32), see Equation 1, using estimates of DF from the ICRP for both the entirety of the respiratory tract and the alveolar section of the respiratory tract, see Equation 2-4. The model, hereafter named the developed mass deposition (DMD) model, requires in in-data from combustion experiments of different biomass fuel types from which the normalised mass size distribution curves has been calculated (under the assumption of a specified density and geometry of the resulting PM). Using Equation 2, the DF is calculated for the diameter range of interest, defined by the mass size distribution curves. By multiplying the resulting normalised mass size distribution curves with the DF curve, a deposited fraction of the normalised mass size distribution curves could be calculated. Then, assumptions regarding respiration rates and volumes, as well as the average exposure for cooking-related combustion of biomass are used. The DMD model requires that the average IAP resulting from each fuel type during cooking-related biomass-combustion is taken into account, see Equation 6. The DMD uses estimations from Eriksson et al (56) for this. For the study population, the defined minute volume for children between 3 and 6 years of age performed by the EPA, is used. The mean average value between passive/sedentary activity and light intensity exertion was chosen as the minute volume, i.e., 7.82 dm^3 per minute, since it was the exertion level seen in a majority throughout the day according to the same EPA document. These values are however unadjusted for weight, describing a population of children (male and female) in the United States of America (49). Under the assumption that the children of the household are equally exposed to IAP as the adults performing the cooking, the model then estimate the deposited dose for the individuals affected by the reduced IAQ from said combustion. The model is described as

$$m_{dep} = \int_{t1}^{t2} \int_{D_{p1}}^{D_{p2}} V \cdot DF \cdot m_0 \cdot X_0 \cdot dD_p \cdot dt \qquad (6)$$

where m_{dep} is the total deposited mass in the respiratory tract, m_0 is the normalised mass deposition curve (describing mass size distribution for arbitrary amount of mass and diameter), V is the minute volume inhaled, t is the time spent cooking (which in this study will be interpreted as the duration of a day's worth of cooking activities), D_p is the aerodynamic diameter of the PM (in this thesis assumed to be a sphere), and X_0 is the IAP mass concentration depending on biomass fuel type usage according to findings by Eriksson et al (56), using average values of measured charcoal, wood, and dung combustion for regular cooking-activities of 315, 7,500, and 16,000 $\mu g/m^3$, respectively. For epidemiological analysis, parameter V must be assumed, while it can also be used for individual values. The value DF, can be used to calculate both deposition of the entire respiratory tract as well as in the alveolar tract, and is calculated using the Equation 2-4 with the assumed inflow of air as < 10

m/s, according to ICRP standards (33). In all, the only data required for the complete model, is the time spent cooking per day and the fuel type.

Calculation of X_0 was done using SMPS data from combustion experiments (56) at the Aerosol laboratory in Lund for the fuel types of coal, wood, and cow dung. The biofuels were brought from Ethiopia and combustion was done the way it traditionally is done. The combustion aerosol was transported into a 23 m^3 stainless steel chamber from where the SMPS sampled. The SMPS data from wood, coal, and cow dung was from three, two, and one separate combustion sessions, respectively. The wood experiments tested three types of wood, named wood1, wood2, and wood3, due to using various SMPS set-ups analysed with 19 scans (15.1 nm to 661.2 nm), 27 scans (10.6 nm to 495.8 nm), and 12 scans (9.47 nm to 414.2 nm), respectively. The two charcoal experiments, charcoal1 and charcoal2, consisted of one SMPS dataset each with 19 and 33 scans, respectively, both across 9.47 nm to 429.4 nm in particle diameters. The cow dung experiment consisted of one set of SMPS data of 13 scans from 15.1 nm to 661.2 nm. The initial dN/dlog(D_p) were converted to a normalised mass size distribution curve (Equation 7), which is described as

$$m_0(D_p) = \left. n_N^0 \cdot D_p \cdot V_c \cdot \rho \right/ \sum_{D_{p0}}^{D_{pmax}} (n_N^0 \cdot D_p \cdot V_c \cdot \rho) \quad (7)$$

Firstly, the lognormal particle number concentration, n_N^0, is used to calculate the approximate PM mass by multiplying with the assumed spherical volume (V_c; calculated by using the mobility diameter), and the particle density of the PM, ρ. In this model, the density is assumed to be homogeneous, and since the mass data in later steps are normalised, the density value is rendered arbitrary in this case. However, in this model, it is assumed to be approximately 1 g/cm^3 for all fuel types, which is conservatively in-line with the studies performed by Kantová et al (44) and Dattamudi et al (43). After this, the arbitrary "particle mass over particle diameter"-curve is normalised over the total mass value, causing the resulting curve's integral, i.e., $\sum_{D_{p0}}^{D_{pmax}} (n_N^0 \cdot D_p \cdot V_c \cdot \rho)$, being equal to 1, resulting in a representation of mass size distribution of the different PM diameters on any given amount of mass for each combustion experiment dataset. To complete the distribution curves of m_0, in the cases where certain section of the distribution was not obtained in the SMPS data, a gaussian distribution fit lwas performed for the unimodal normalised mass size distribution curves, while a non-linear regression approach was adapted for multimodal curves, both across the diameter ranges of 10 nm to 2 µm. Using the MATLAB curveFitter function, new curves portraying the entire normalised mass size distribution curve could be modelled for the relevant span of diameter values using extrapolation. By combining these curve functions with Equation 6, an estimated mass size distribution (m_{dep}) was obtained for each SMPS dataset. The particle diameter values, D_p, are described by the extrapolated curve values from the curve fitting from the SMPS measurements from the combustion experiments. The resulting m_{dep} estimate for each experiment dataset was subsequently compiled to one average value for each fuel type.

The household is interpreted as a confined, limited space in which the constituents are well-mixed, meaning that the same concentration will be present throughout the volume of the household. For many models, a volumetric flow into and out of the volume of interest are required. Since these flows are difficult to assess, the DMD model will instead rely on the air exchange rate (AER). The AER average of homes in Ethiopia has been calculated using data from previous studies in Ethiopia (27),

and the resulting AER was later used in the combustion-experiments (56). The combustion experiments describe an average air pollution level throughout the entire combustion period, which will be used in estimations of exposure. We have chosen to disregard the further persisting air pollution after the combustion has been finished, due to the relatively high AER of 15 h^{-1}. The DMD model have a one-chamber assumption of the household, i.e., houses with several rooms will still be interpreted as a single compartment that is well-mixed. Since the household is assumed to be a well-mixed environment as well as a one-chamber compartment, it is assumed that the total time of cooking affects every individual being inside of the house during cooking equally, even if the individual in question is not at the cooking station.

4.1 Statistical analysis

The study intends to estimate mass deposition of the PM, which require modification of Equation 2 using data from the combustion experiments conducted in Lund to construct the mathematical model. With a limited amount of in-data, the model's task is to estimate the mass deposition arising from cooking-related biomass-combustion. An initial test of the DMD model (using analysis of variance [ANOVA]) was done to investigate if statistically significant differences can be seen for the estimated mass deposition between different fuel type usages. Additionally, a paediatric cohort of children below five years of age, was analysed. The assessment was done based on the DMD model and on collected information on e.g., cooking habits from the cohort. Initial data management was performed in STATA. Subsequent statistical analysis was also performed in STATA, using ANOVA analysis to compare difference between estimated deposited mass for different fuel type usage groups, while binary logistic regression was used to investigate the association between the modelled deposited mass and adverse health outcomes for the pre-study cohort population. Additionally, by including other parameters of interest and suspected confounders, analysis in both univariate and multivariate logistic regression was performed. For this thesis, the DMD model's estimate of deposited mass along the entire respiratory tract and in the alveolar tract are the main variables of interest, hence these were treated as continuous variables. Other parameters used either in comparison or on their own are time spent cooking (measured in hours, treated as a continuous variable), smokers in the household (treated as a binary variable), incense usage in the household (treated as a binary variable, where the options "rarely" and "sometimes" are both treated as the value 1 and the option "never" was treated as the value 0), fuel type usage (treated as a categorical parameter, of wood, charcoal, or cow dung), and fever symptoms in children residing in the household aged less than five years old (treated as a binary variable). The outcome of interest was respiratory symptoms in children in the household aged less than five years old, which was treated as a binary variable. In the case where data was missing regarding fuel type usage, time spent cooking, or health outcomes, the household was excluded from the analysis.

4.2 Study setting and cohort details

The study population lies in an area in the eastern parts of Oromia, collected from several kebeles (sub-districts) around the city of Haramaya (57). In total, the district of Haramaya, where the city of Haramaya is included, accounts for approximately 310,310 individuals. With 12 of 34 kebeles represented in the area (57), the study area is adequately representative of the total population of the region. The Haramaya health and demographic surveillance system (Haramaya HDSS) (57) initiated in 2018 in eastern Ethiopia, with a goal of enabling data for population health and demographic

analysis. With a total initial study population of 99,898 individuals and over 17,000 households, the study population can provide sufficient statistical power to detect small (5 %) effects. In our analysis, only respondents having the input data (i.e., time spent cooking and fuel used for cooking), demographic (i.e., household pseudo-ID and location pseudo-ID), and adverse health outcome (respiratory and fever symptoms, as well as confounding variables smoking and incense usage) were included in the subsequent analysis. Given large (orders of magnitude) differences in air pollution levels from different types of solid biofuels (56), the exposure levels can be estimated for each individual in the household. The health outcomes of interest for this study were focused on the paediatric population of the household, aged less than 5 years old, where respiratory and fever symptoms as the outcome of interest. Other variables that will be of interest are confounders such as smokers in the household and incense usage.

5. Results

5.1 Calculating m_{dep} using the developed mass deposition model

The normalised mass size distributions from the fuel collected on-site, and later combusted at laboratory in Lund, can be seen in Figure 3. The different types of wood shows variation in mass size distribution for particles larger than 0.1 micrometre, where two curves (wood2 and wood3) exhibit a unimodal appearance while the curve for wood1 appears multimodal with an initial peak at smaller PM diameters. Regarding the charcoal curves both have a unimodal appearance, with similar PM diameter ranges. Dung, which has only one experiment represented, shows a multimodal distribution profile of PM, with an initial peak at smaller PM diameters.

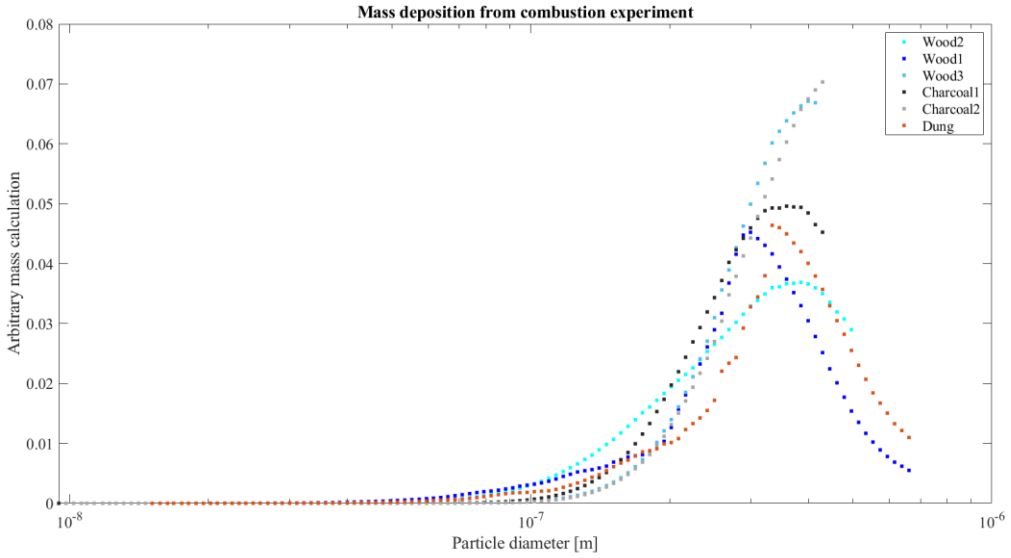

Figure 3: Normalised mass size distribution of particles from combustion experiment at Lund Aerosol laboratory.

Using MATLAB, unimodal distributions (i.e., wood2, wood3, charcoal1 and charcoal2) were fitted according to a Gaussian distribution, while multimodal size distributions (wood1 and cow dung) were fitted according to a non-linear curve fit using linear interpolation (Figure 4a and 4b). The resulting curve functions can be seen in Table 1, with R-squared values all showing a fit above 0.9.

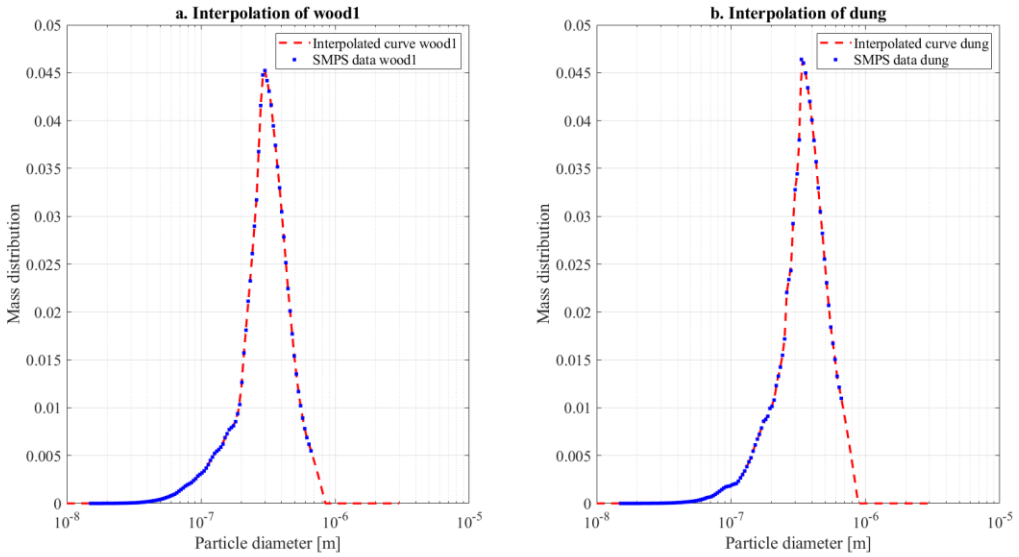

Figure 4: The interpolated curves constructed from SMPS data from combustion of wood1 (a) and dung (b), seen in subfigure a and b, respectively.

Table 1: Functions describing the mass size distribution curves from combustion of different biomass fuels

Fuel type	Function	R-square
Eucalyptus	$m_0(D_p) = 0.03534 \cdot e^{(-((\log(x)+6.424)/0.3573)^2)}$	0.9978
Charcoal E	$m_0(D_p) = 0.07161 \cdot e^{(-((\log(x)+6.33)/0.2786)^2)}$	0.9999
Charcoal A	$m_0(D_p) = 0.04994 \cdot e^{(-((\log(x)+6.448)/0.2563)^2)}$	0.9999
Wood	$m_0(D_p) = 0.06724 \cdot e^{(-((\log(x)+6.39)/0.2438)^2)}$	0.9998
Mila	Non-linear curve fit	1
Dung	Non-linear curve fit	1

Using the functions listed in Table 3, normalised curves over the PM diameter range of 10 nm to 2 µm, with 10 nm intervals were calculated, see Figure 5, ensuring a full view of all mass size distribution in the experimental combustion data. These curves show differences in how broad each experiments' PM mass size distribution is and that the size distributions of charcoal, dung and wood, are largely overlapping. Noteworthy is the increased mass portion of particles of smaller diameter for wood2 combustion, as well as the increased mass portion of particles of larger diameter for wood3 and charcoal2, compared to other fuel types.

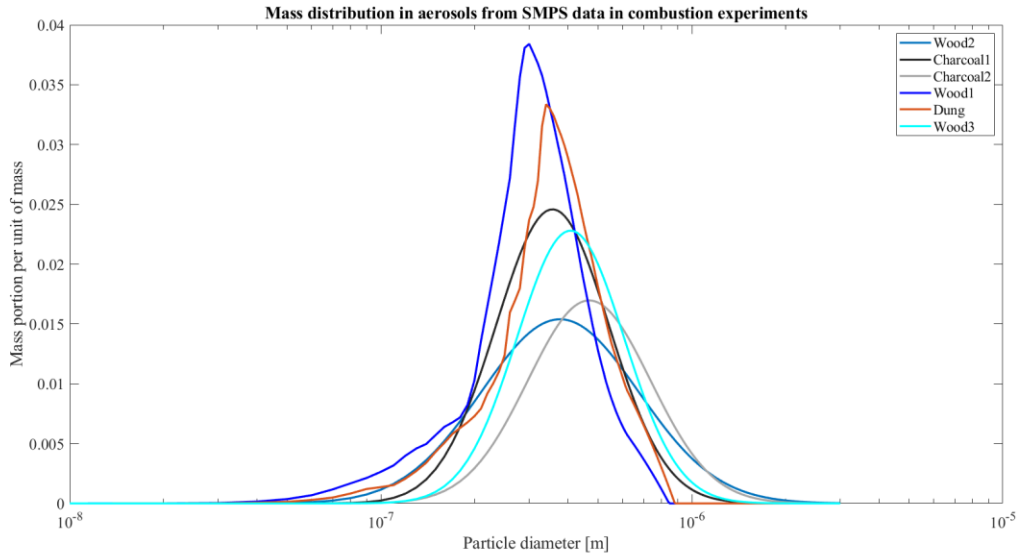

Figure 5: Normalised mass size distribution curves for resulting PM from cooking-related aerosol combustion experiments in which mass size distributions curves has been calculated and extrapolated.

5.2 Deposition model

The DF for the total respiratory tract was modelled using Equations 3-4, over the diameter range 10 nm to 2 µm. Additionally, the DF of the alveolar part of the respiratory tract was modelled using Equations 3 and 5.

When the DF of the total respiratory tract across the investigated diameter range is multiplied with the mass size distribution curve, see Figure 6 and 7, the result shows the fraction of a given mass that is deposited along the respiratory tract. The resulting curves show skewing of the distribution curves, see Figure 6. Notably, some curves are more affected by the multiplication of DF than others, mostly the curves exhibiting a wider range of particle diameters, e.g., the wood2 curve.

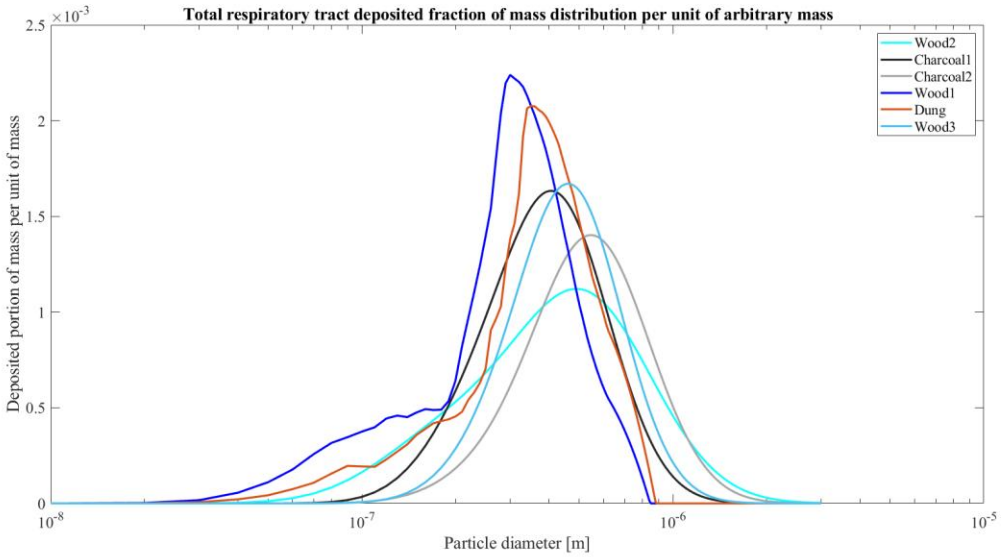

Figure 6: Deposited fraction of an arbitrary mass, for each fuel type that is used as in-data for the DMD model.

Regarding the alveolar distribution, when combined with the normalised mass size distribution curves, similar skewing (possibly a larger constituent of smaller diameter aerosols) is noted, however, of course with lower deposited mass portion values, see Figure 7.

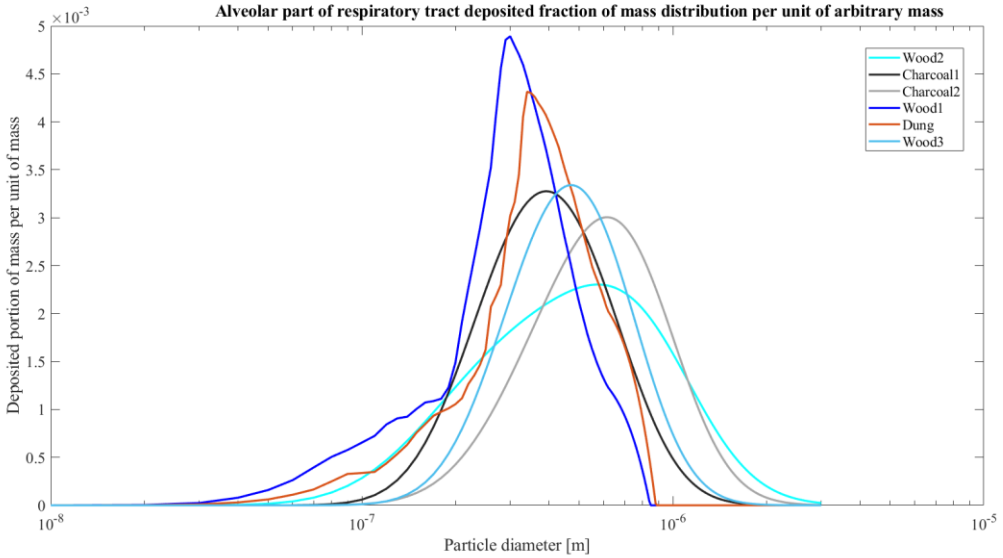

Figure 7: Deposited alveolar fraction of an arbitrary mass, for each type that is used as in-data for the DMD model.

After calculating the mass size distribution curves of deposited fraction of inhaled PM mass for each fuel type, and after including exposure data in Equation 6, a deposited mass is ready to be estimated for each normalised mass size distribution curve.

5.3 Model application for Ethiopian cohort

As an initial trial for the DMD model, it was applied to a study population from the Haramaya HDSS cohort. The study population underwent data management, with an initial population of 4,583 individuals. After these data management steps, see Figure 8, a cohort of 1,762 participants remained, see Table 2, consisting of three groups depending on what fuel type, i.e., charcoal, wood, and dung, is used, see Table 3.

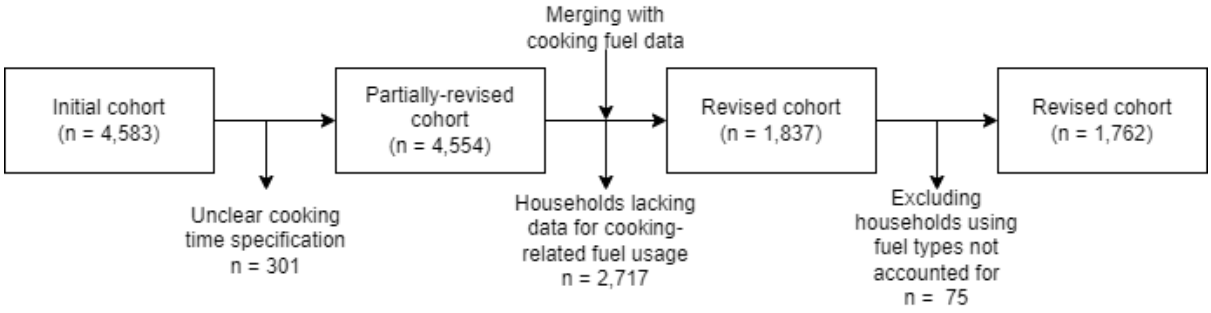

Figure 8: Data management steps of the study population.

Worth noting is that if an individual combust these fuels using open-fire cooking in the on-site setting described by Edlund (27), and thus becoming exposed to the IAP estimated by Eriksson et al (56), it only takes a few minutes when using the most polluting fuel types to surpass the health guidelines for 24 hour average PM2.5 exposure set by the WHO (5), i.e., 15 $\mu g/m^3$. By averaging the different estimated values for each fuel type, namely charcoal, wood, and dung (56), the mean aerosol concentration at an AER of 15 h^{-1} is found to be 315, 7500, and 16,000 $\mu g/m^3$, respectively. This results in reaching the 24 hours WHO guidelines, after using 100 g of biomass fuel, after approximately 1.14 hours, 0.05 hours, and 0.02 hours, for charcoal, wood, and dung, respectively, hence, signifying that most of the cohort being above the 24 hour average PM2.5 exposure guidelines by the WHO (5).

Time spent cooking in the cohort varies, but the subgroups (depending on fuel type usage) show a similar average of 4.1 hours per day (standard deviation [SD] of 1.48 hours). The entire cohort has a similar percentage of children living in the household aged less than five years experiencing respiratory symptoms (approximately 27 %), the same is true for the percentage of children aged less than five years old experiencing fever symptoms (25 %), see Table 2. When dividing the cohort into subgroups based on fuel type usage, see Table 2, the time spent cooking per day is similar, hence duration of cooking is not dependent on the fuel type being used. A notable difference in population size was noted with 8, 1,730, and 24 households using charcoal, wood, and animal dung usage, respectively. The low population numbers of particularly the charcoal subgroups could be a limit to the statistical analysis and is probably a cause for concern in regard to statistical power. Differences between subgroups were noticed (Table 2) for the parameters incense usage, smoker in household, and the two health outcomes (fever and respiratory symptoms). The subgroup using dung as fuel had the highest prevalence of respiratory and fever symptoms, while it had the lowest prevalence of incense usage, see Table 2. The subgroup using wood had the lowest prevalence of respiratory symptoms and smokers in the household, while it had the highest (together with the charcoal subgroup) prevalence of incense usage. Due to the previously described low size of the charcoal cohort, it is unclear what significance the presented data of the charcoal subgroup presents.

Table 2: Summary of the study cohort, standard deviations (SD) shown in parentheses.

Category [unit of measure]	**Mean average (n = 1,762)**
Time spent cooking [hours per day]	4.11 (1.48)
Fuel types used for cooking	
- Coal	8 (0.45 %)
- Wood	1,730 (98.2 %)
- Animal dung	24 (1.36 %)
Smoker in household	
- Yes	764 (43.4 %)
- No	998 (56.6 %)
Respiratory symptoms of children less than 5 years of age in household	
- Yes	469 (26.6 %)
- No	1,293 (73.4 %)
Fever symptoms of children less than 5 years of age in household	
- Yes	439 (24.9 %)
- No	1,323 (75.1 %)
How often do individuals smoke incense while boiling coffee?	
- Yes	1,291 (73.3 %)
- No	471 (26.7 %)

Table 3: Usage of different fuel types in the study cohort. Standard deviations (SD) and percentage values are shown in parentheses.

Category	**Charcoal (n = 8)**	**Wood (n = 1,730)**	**Dung (n = 24)**
Time spent cooking [hours per day]	4.13 (1.25)	4.11 (1.48)	4.29 (1.33)
Smoker in household			
- Yes	6 (75.0 %)	744 (43.0 %)	14 (58.3 %)
- No	2 (25.0 %)	986 (57.0 %)	10 (41.7 %)
Respiratory symptoms of children less than 5 years of age in household			
- Yes	3 (37.5 %)	455 (26.3 %)	11 (45.8 %)
- No	5 (62.5 %)	1,275 (73.4 %)	13 (54.2 %)
Fever symptoms of children less than 5 years of age in household			
- Yes	2 (25.0 %)	423 (24.5 %)	14 (58.3 %)
- No	6 (75.0 %)	1,307 (75.5 %)	10 (41.2 %)
How often do individuals smoke incense while boiling coffee?			
- Yes	6 (75.0 %)	1,277 (73.8 %)	8 (33.3 %)
- No	2 (25.0 %)	453 (26.2 %)	16 (66.7 %)

The average value of deposited mass in the respiratory tract (both as a whole and only the alveolar part) for this cohort was calculated for each individual based on the self-reported cooking activities of the household. The results are shown in Table 4. Charcoal combustion for the study participants showed an estimated daily deposition of approximately 128 µg (SD 38.8 µg) for the total respiratory tract and 51.5 µg (SD 15.6 µg) for the alveolar section of the respiratory tract. Wood combustion showed an estimated daily deposition of approximately 2,850 µg (SD 1,030 µg) for the total respiratory tract and 1,170 µg (SD 421 µg) for the alveolar section of the respiratory tract. Finally, for combustion of animal dung, the estimated deposition was found to be 5,230 µg (SD 1,630 µg) for the total respiratory tract and 2,420 µg (SD 755 µg) for the alveolar tract.

Table 4: Estimated mass deposition for the different subgroups within the study population

Fuel type category	Charcoal (n = 8)	Wood (n = 1,730)	Animal dung (n = 24)
Estimated mass deposition along the entire respiratory tract [µg] (SD)	128 (38.8)	2,850 (1,030)	5,230 (1,630)
Estimated mass deposition along the alveolar portion of the respiratory tract [µg] (SD)	51.5 (15.6)	1,170 (421)	2,420 (755)

The estimated mass deposition for each subgroup (based on fuel type usage) of the cohort was analysed using ANOVA to investigate if the different mass deposition estimates were statistically significant between the subgroups. The ANOVA shows clear differences between the different fuel usage groups estimated mass deposition, with a p-value < 0.0005 for both the deposition of the entire and alveolar section of the respiratory tract, indicating a statistically significant difference between the estimated mass depositions provided by the model.

5.4 Diameter specific particle number deposition analysis

The DMD model also allows for estimates regarding the number deposited particles within a specified size range. For ultrafine PM, a conservative count of the total particle number deposition was performed by assessing the total amount of ultrafine particles being deposited in the entire respiratory tract as well as the alveolar part of the respiratory tract. This was performed by dividing the mass size distribution curve (Figure 6 and 7) with the mass value of a PM particle with the previously specified density and particle number concentrations for particles less than 100 nm in aerodynamic diameter. The result, see Table 5, indicate estimates of at least tens of trillions of ultrafine particles are deposited, where the estimated number increases with decreasing energy density of the used fuel type, both for the entire respiratory tract and the alveolar part. For the entire respiratory tract and the alveolar part, deposition of ultrafine charcoal, wood, and animal dung particles are tens of trillions, tens of quadrillions, and hundreds of quadrillions, respectively, each day.

Table 5: Estimated deposited PM particle number (PM < 100 nm) for both the entire respiratory tract and the alveolar part.

Deposition location	Charcoal (n = 8)	Wood (n = 1,730)	Animal dung (n = 24)
Total respiratory tract [Particle number] (SD)	1.0 E14 (3.0 E13)	9.4 E16 (3.4 E16)	2.4 E17 (7.4 E16)
Alveolar part of the respiratory tract [Particle number] (SD)	6.0 E13 (1.8 E13)	6.2 E16 (2.2 E16)	1.6 E 17 (4.8 E16)

When ANOVA is used to investigate statistical significance between the fuel type usage subgroups, a clear statistical significance between the estimated deposited ultrafine particle number is noticeable for this dataset, with a p-value of < 0.0005 for both total and alveolar respiratory tract deposition.

5.5 Example of model application in epidemiological setting

Finally, the DMD model was also tested with health outcomes, to highlight its epidemiological application possibilities. The statistical analysis was performed for both mass deposition estimates, i.e., the entire respiratory tract as well as the alveolar part, investigating correlations, using both univariate and multivariate analysis.

5.5.1 Univariate analysis

The univariate logistic regression showed statistically significant correlations with respiratory health outcomes for several factors (Table 5).

For respiratory symptoms in children under 5 year of age, a correlation with: an increased risk of respiratory symptoms with smokers present in the household (Odds ratio [OR] 1.26 with a 95 % confidence interval [CI] between 1.02 and 1.56); an decreased risk for respiratory symptoms and longer cooking times (OR of 0.88, with 95 % CI between 0.82 and 0.95); a decreased risk for respiratory symptoms and lower estimated mass depositions, both for the entire respiratory tract (OR of 0.99986, with 95 % CI between 0.9998 and 0.9999), as well as for the alveolar portion of the respiratory tract (OR of 0.9997, with 95 % CI between 0.9994 and 0.9999); an increased risk of respiratory symptoms when using animal dung compared to wood (OR 2.37, with 95 % CI between 1.05 and 5.33), while indications for the same increased risk was noted for charcoal (OR 1.68, with a 95 % CI between 0.40 and 7.06); an increased risk for respiratory symptoms was also noticed for fever symptoms (OR 9.17, with a 95 % CI between 7.18 and 11.71). No correlation was noted for incense usage in the household (OR of 0.92, with a 95 % CI between 0.73 and 1.17).

Table 5: Univariate logistic regression between different parameters of the study cohort and the health outcome of interest, i.e., respiratory symptoms of children aged less than five years old. The table shows Odds ratio, Confidence interval, p-value and pseudo-R-squared value of the analysis.

Category	Odds Ratio	95 % Confidence interval	P-value | Pseudo R^2-value
Time spent cooking	0.88	0.82 – 0.95	0.001 | 0.0058
Fuel type category compared to wood			
- Charcoal	1.68	0.40 – 7.06	0.478 | 0.0023
- Animal dung	2.37	1.05 – 5.33	0.037 | 0.0023
Estimated deposited mass for entire respiratory tract	0.9986	0.9998 – 0.9999	0.004 | 0.0041
Estimated deposited mass for alveolar portion of respiratory tract	0.9997	0.9994 – 0.9999	0.009 | 0.0034
Smoker in the household	1.26	1.02 – 1.56	0.033 | 0.0022
Incense usage in the household	0.92	0.73 – 1.17	0.493 | 0.0002
Fever symptoms for children in the household with an age less than five years old	9.17	7.18 – 11.71	< 0.005 | 0.1669

5.5.2 Multivariate analysis

The multivariate analysis provides results for both estimated mass deposited along the entirety of the respiratory tract as well as for the estimated mass of the alveolar portion of the respiratory tract, with correlation analysis for respiratory symptoms of the children aged less than five years old residing in the household of the cohort. For respiratory symptoms, multivariate analysis was performed for the estimated deposited mass along the entire respiratory tract, as well as for the estimated deposited mass for the alveolar portion of the respiratory tract. To avoid multivariate analysis concerning parameters with high correlation coefficient, either the time spent cooking parameter or the estimated mass deposition parameter was omitted to achieve better estimate on both parameters' influence on the health outcomes, due to high covariance between the two parameters. A medium-level covariance was noted for the health outcome *fever symptoms*, resulting in multivariate analysis both with and without this parameter.

With a pseudo R^2 – value of 0.01 for both entire and alveolar respiratory tract mass deposition estimates, the multivariate analysis (with time spent cooking and fever symptoms omitted) provided correlation findings for both analyses. Starting with the estimate for mass deposition along the entire respiratory tract, shown in Table 6, statistically significant correlations (P-value < 0.05) were noted for the total respiratory mass deposition (OR 0.9998, 95 % CI between 0.9998 and 0.9999), animal dung usage compared to wood (OR 3.48, 95 % CI between 1.47 and 8.24), and smokers in the household (OR 1.26, 95 % CI between 1.02 and 1.57), while no statistically significant correlation could be seen for incense usage. For the mass deposition estimate regarding the alveolar portion of the respiratory tract, see Table 7, statistically significant correlations (P-value < 0.05) were noted for the

alveolar respiratory mass deposition (OR 0.9996, 95 % CI between 0.9994 and 0.9998) animal dung usage compared to wood (OR 3.92, 95 % CI between 1.62 and 9.50), and smokers in the household (OR 1.26, 95 % CI between 1.02 and 1.57), while no statistically significant correlation could be seen for incense usage and fuel type usage. Multivariate analysis omitting mass depositions and having time spent cooking instead in the analysis showed only statistically significant correlation with the parameter smokers in household (data not shown).

Table 6: Multivariate analysis for the entire respiratory tract deposition estimate, showing the Odds ratio, 95 % confidence interval, and p-value, for correlation between the below seen parameters and respiratory symptoms of children living in the study population household aged less than five years old, showing pseudo R^2 – value of 0.0104.

Category	Odds Ratio	95 % Confidence interval	P-value
Estimated mass deposition of the entire respiratory tract	0.9998	0.9997 – 0.9999	< 0.005
Fuel type used as fuel instead of wood			
- Charcoal	0.96	0.22 – 4.14	0.954
- Animal dung	3.48	1.47 – 8.24	0.005
Smoker in household	1.26	1.02 – 1.57	0.031
Incense usage in household	0.95	0.74 – 1.20	0.644

Table 7: Multivariate analysis for the alveolar deposition estimate, showing the Odds ratio, 95 % confidence interval, and p-value, for correlation between the below seen parameters and respiratory symptoms of children living in the study population household aged less than five years old, showing pseudo R^2 – value of 0.0103.

Category	Odds Ratio	95 % Confidence interval	P-value
Estimated mass deposition of the alveolar portion of the respiratory tract	0.9996	0.9994 – 0.9998	0.001
Fuel type used as fuel instead of wood			
- Charcoal	0.96	0.22 – 4.17	0.961
- Animal dung	3.92	1.62 – 9.50	0.003
Smoker in household	1.26	1.02 – 1.57	0.031
Incense usage in household	0.95	0.74 – 1.20	0.644

When introducing the fever parameter into the multivariate analysis, no statistical significance (i.e., p-value < 0.05) can be seen for parameters other than fever symptoms, both for estimated mass deposition for the entire respiratory tract (for fever symptoms correlation with respiratory symptoms, OR 9.1, 95 % CI between 7.05 and 11.6, p-value < 0.0005) and for the alveolar portion of the respiratory tract (for fever symptoms correlation with respiratory symptoms, OR 9.1, 95 % CI between 7.06 and 11.6, p-value < 0.0005). Additionally, when excluding charcoal, and performing

multivariate analysis, no additional statistically significant variables were noted, and the previously noticed statistically significant variables remained, although with slightly different values for Animal dung (OR 3.93, with 95 % CI between 1.62 and 9.53) and Smoker in households (OR 1.25, with 95 % CI between 1.01 and 1.55).

6. Discussion

This is a first attempt to model the mass deposition of combustion-related PM in the respiratory tract of household residents in a low-income setting in order to improve indoor exposure assessment. Hopefully, this may inspire more research to further nuance and advance the connections between IAP and health. This study highlights a scientific area and epidemiological setting outside of Europe or the United States of America. Similar models has, to the writer's knowledge, not been attempted to be applied in this context, thus it is an attempt to investigate the issue of IAP in an innovative manner. This study relies on combining the results from several previous studies, such as studies that has conducted on-site measurements and combustion experiments using samples collected on-site. Furthermore, I use demographic data collected collected in a structured and professional manner, providing diversity and relevance to the study.

By the health guideline standards of WHO (5), advising not more than 15 $\mu g/m^3$ as a 24-hour average IAP exposure, none of the households of the present study would be following this guideline due to indoor biomass-combustion alone. The DMD model was able to estimate lung deposited particle doses (both mass and number) of the cohort individuals, showing adaptability in assessing both mass and number depositions, as well as the possibility to focus on any PM diameter range of interest. The estimated values from ANOVA, both for particle mass and particle number deposition, for each subgroup of the cohort, divided by fuel type usage, are shown to be significantly different from each other. This indicates that there is a clear difference in the level of PM that is deposited in the respiratory tract, depending on what fuel type that is used. Furthermore, the model shows several potential applications for estimating different exposure, depending on households' habits, allowing for epidemiological studies regarding the indoor PM deposition (both mass- and number-wise) in the human respiratory tract. Nanoparticles, i.e., ultrafine particles (< 100 nm) has been under investigation for correlations with several different health ailments, described by Schraufnagel (58) among others. It has been shown that exposure for other nanoparticles, such as silver nanoparticles, can induce toxicity and inflammation in respiratory epithelial cells (59). Additionally, interactions between nanoparticles may interestingly alter the cytotoxicity of other nanoparticles (60). In the book "Assessing Nanoparticle Risks to Human Health" (61), it is requested that further toxicological studies should be made since chemical, physical, and biological properties of nanometre-sized particles can be different than those of larger particles. In this case, I would agree that further studies regarding the different nanoscale biomedical effects of nanoparticles created by biomass-combustion would be another interesting aspect to investigate, especially if performed on on-site harvested biomass fuels where the target exposure level can be estimated using the DMD model and then replicated in a toxicological testing. Additional effects to consider in future studies is further description regarding the composition of the resulting PM when combusting biomass fuels, and to investigate if an increased health risk can be noticed for certain compositions. This model allows for analysis of the specific mass and number deposition of ultrafine nanoparticles, both in the total respiratory tract and the alveolar section of the respiratory tract, with many promising applications, both for epidemiology, personalised health care, and biomedical experiments.

It is vital when constructing models to be aware of the assumptions that has to be made for the model to be operational. The initial estimate for the combustion experiment by Eriksson et al (56) was the assumption of AER at 15 h^{-1}, based on the exposure measurements by Edlund (27). The AER is an

average value from 26 on-site measurements and is, even though to date it is the most comprehensive assessment of AER in Ethiopian homes, a rough estimate of the ventilation capabilities of households in Ethiopian households, conducted in the same country as the cohort that was used for this thesis, albeit not in the same region. The assumption that the IAP is only accounted for during the cooking time, not taking the persisting PM emission from residual fuel in the stove into account, is deemed appropriate still due to the high AER reducing the PM concentration rapidly. The model is based on average AER values and that cooking practices are the same, although these of course vary in the real world.

By elaborating on the proposed future emissions from the International Energy Agency (IEA) from 2009 (62), and reviewing implementing policies proposed in a study conducted by Amann et al evaluating effects of mitigation projects on air pollution (63), Anenberg et al calculated that up to 4.4 million household PM2.5 associated annual deaths could be avoided indicating benefits from restricting air pollution that could originate from household combustion-related activities (64), while basing the health effects of the air pollution from a study conducted Shindell et al (65). Further studies from Wilkinson et al (66) focusing on housing energy shows that combustion of biomass has direct environmental and health-related effects on individuals in the household, but also on the local area and globally. Healthwise, estimates showed clear reductions in disease burden when improving household ventilation and when fuel is switched. Wilkinson et al (66) performed a case study using data from India, where it was estimated that the health benefits of switching stoves could reduce the total number of disability-adjusted life-year (DALY) for acute lower respiratory infections, chronic obstructive pulmonary disease, and ischaemic heart disease, by 30.2 %, 28.2 %, and 5.8 %, respectively, showing that AER values and stove type has a clear impact on the health and is therefore an important parameter to estimate with precision. Assessing exposure during different AER in laboratory settings could thereby further nuance the model accuracy, and thereby the exposure assessment. Factors such as the number of windows, and ventilation time (time when windows are open) could be of interest in that case, although it would be more difficult to establish and collect data that could be useful in that context, since it requires a more cohort in-data, thus reducing the easy-to-use aspect of this model where it, at this moment, only requires a limited number of input variables, allowing for easier data sampling and modelling of a broader population, which is helpful for studies in low-income settings. Emission factors (mass of IAP generated per mass unit of biomass) could be used in the DMD model, however, yet again, the model would be more demanding in terms of the collected in-data. The difference in IAP level depending on stove type is of course a confounder that would be interesting to be aware of in future studies. A systematic review conducted by Thomas et al. (67) found that exposure levels could be reduced when implementations were adequately used, however, many compliance issues with persisting in using only improved stoves occurred as well.

There may also be other aspects regarding the ICRP model to investigate in future studies. For example, the total lung surface area applied in it, is for an average 176 cm tall male, which is assumed to be circa 78 square metres (68). However, regarding the surface area of the lung, the precise number is contested. Fröhlich et al (69) has described the variation of surface area for the lung throughout the breathing cycle, where sources differ in which values are estimated, spanning from 70 to 180 square metres in size. For children, which the model was tried on, an altered minute volume for breathing has been observed, as well as changes in the deposition fraction depending on the age of the individual, however, only after compensating for the lung volume itself (70), which is vital to be aware of and

which would be interesting to further investigate. Worth knowing is that the study population that was included for ICRP study (33) was a homogeneous group of caucasian males, where parameters for other genders or paediatric ages where estimated only by scaling. With these raised concerns, the ICRP model has still been shown to estimate deposition as well as other more complex models (71, 72) and was therefore chosen for this study. This is of course also an aspect to consider as well when discussing the subsequent model's comparability with the deposition of PM in the respiratory tract of e.g., children in Ethiopia. Although ICRP discuss the possible differences in respiration that could be present when implementing the model on other individuals than Caucasian males, it does not give any precise instructions on how the model can be adapted. A model based on a more diverse study population, both in terms of gender and background, could result in a more precise model for different study populations which of course would be a welcome addition for this study. Pritchard et al (73) has described that there may be a gender difference that can affect upper airway deposition, resulting in a greater deposition for women than for men. Kim et al (74) has described that the opposite may be true for deposition of the deeper airway, where greater deposition may be seen than for women. Regarding the assumed respiratory parameters, the data provided by the EPA describes the respiratory capabilities of children across the ages 3 to 6 years old, which is later compared to health outcome data of children aged less than 5 years old in the cohort households. Of course, there is a discrepancy between the two different parameters age range, which is a source of error worth being aware of when interpreting the data. Another aspect to consider is that the EPA data is collected from a high-income country, i.e., the United States of America, and is later compared to an overall less wealthy country, i.e., Ethiopia. This is another perspective than can be argued as a source of error, especially since the data is unadjusted for the weight of the children in question. Additional details that could grant the model further nuance is if factor such as aerosol deposition affecting diagnoses could be included into the analysis. Although there are less evidence of this in literature, Frampton et al has shown (75) that individuals with asthma has a higher deposition of certain PM compared to healthy individuals. This shows that further research is needed to evaluate the deposition of PM for individuals suffering from respiratory illnesses such as asthma but also chronic obstructive pulmonary disease. When such data is produced in the future, it can easily be added to the DMD model. The increased deposition tendency could implicate a higher deposited dose in these individuals compared to healthy individuals during equal exposure levels. As noted in the information released by the EPA (49), the minute volume of a breath is affected by an individual's age and is also a source of error for this model. The questionnaire that the DMD model try-out relies on, does not provide any further information regarding the children experiencing respiratory symptoms, other than that the individual in question is aged less than five years old. If more facts were present in these instances, perhaps a more precise model could be achieved were chronical respiratory diagnoses and more precise minute-volume assumptions can be made. Additionally, bearing in mind that other studies, e.g., Rissler et al (76), Asgharian et al (70), and Olvera et al (77), also indicate that changes may occur in the DF curve for individuals depending on their age, it is also of interest to know more about the study participants in this sense. In the perspective of future studies investigating the model's application in estimating predisposition of adverse health effects in households in low-income countries, other perspectives are raised. Many pregnant individuals for example may have respiratory diagnoses as well, highlighting further need of studies in our study participant cohort. Likewise, pregnant individuals may have respiratory changes without having previous respiratory diagnoses, especially at later stages of pregnancy when the foetus may temporarily alter breathing physiology(78). The ICRP-defined deposition of the ultrafine particle fraction has also been questioned since experimental values of show an increased deposition compared to the ICRP model(79), resulting in certain studies relying on scaling of the DF for particles in the smaller diameter range(32). For this study, estimates were made showing significant differences between fuel type usage for smaller particles as well, however it

would be interesting to evaluate what effects would come from this change. Likewise, another aspect of particle characteristics is the particle absorption of water vapour, which can affect the deposition of PM in the human respiratory tract, according to Löndahl et al (80), showing another perspective that would be interesting to include into this model. Furthermore, a model reviewing and improving the modelling of interstitial deposition and long-term persistent deposition has been described by Kuempel et al (81, 82), which would be an interesting concept if the study question should try to factor in exposure and deposition before pregnancy as well.

Regarding the PM, there are also assumptions worth discussing. Further opportunities in improving the study results can be found in the precision and complexity of the deposition model. The PM in this case was modelled as spheric particles, an estimate that could be improved for future studies. Of course, other geometric shapes could be used to describe the PM, to ensure that the geometry of agglomerated aerosols, which is the most likely morphology of combustion-generated particles, can be estimated. Another assumption that could be further explored and refined is the particle density. In this study, a homogeneous density is assumed for all PM. A future perspective to be investigated could be to model the variation in density based on particle size and fuel type. Another aspect necessary to consider is the limited number of combustion experiments that are used as in-data for the model. Here, a welcome addition for future studies would be to include more replicates of the combustion experiments for the different biomass fuel types as this would reduce the risk of outlier experiment result and subsequent skew of modelling parameters. More experiments would also provide better precision in what level of air pollution that is expected for each fuel type.

The application of this model relies on self-reported data, causing a source of error related to how individuals interpret the different questions. Respiratory symptoms may be interpreted differently, and not all respiratory symptoms are necessarily related to or correlated with indoor air pollution, causing difficulties in the analysis segment of this thesis. Furthermore, other confounding parameters not being present in this study are ambient air pollution and other combustion-related activities in the household of the study cohort. Starting with ambient air pollution, this is of course something that would be of interest in the statistical analysis section of this thesis, since it most likely varies over the the Haramaya district in which the cohort is situated. Households located near major roads, polluting industries, or in more densely populated areas, will experience a higher degree of ambient air pollution. It would be a welcome addition to differentiate and locate possible effects from the indoor cooking-related activities, and separate the adverse health effects from IAP and ambient air pollution. Secondly, regarding the other combustion-related activities in the household of the study cohort, unclarities regarding these activities prevented analysis regarding the deposited mass in the respiratory tract, which would be a welcome addition to this study. Finally, while the cohort provided the frequency of, e.g., coffee making per day and fuel type used, it was unclear whether the coffee making was performed in the same combustion event as the food cooking or not. More information regarding these and other combustion-related activities, e.g., for heating or lighting, would be needed to further nuance the analysis and prevent skewing and bias due to certain pollution exposures not being accounted for.

When the DMD model was tried out by analysing correlations between deposition of PM and respiratory symptoms in children aged less than five years old in the household, the result is in

contrast to what one would expect to be seen since it indicates that higher deposited mass is correlated to reduced presence of respiratory symptoms. This unexpected result, can be caused by several different aspects by their own or at once. Potentially, the DMD model assumes the situation correctly, however, one might argue that it is unlikely that the children of the household are exposed during the entire duration of the cooking session. The children are probably not involved in all the cooking activities and could therefore be assumed to also spend time outdoors during the cooking event. Another reason is that other key information is lacking (such as other combustion related activities, changes in fuel type that is used, outdoor air pollution) or that information has been misinterpreted when filling out the questionnaire. The questionnaire allows for a broad interpretation and cough/respiratory symptoms can have many different aetiologies. Therefore, more background health information could be helpful addition for future health analysis using this model, to avoid other non-PM-related respiratory ailments to be interpreted as PM-related in the questionnaire. Another assumption that could explain the correlation, is that the same amount of air pollution was present as long as the same fuel type was used. This assumption could be argued, since the local method of combusting, mass being used, and other parameters, could influence the exposure and subsequent mass deposition. Additionally, the OR is very close to 1, indicating that the estimated impact of the deposited mass is in this context low. Focusing more on the confounders, we also found that correlations with smokers in the household are noticed with an increased risk of respiratory symptoms of the children in the household, showing the continued need of having this parameter present in future statistical analysis. Incense usage was not seen to be correlated with respiratory symptoms, with a p-value > 0.05, indicating that further studies are needed to gain clarity in its possible effects, which has been hypothesised by, e.g., Shrestha (83). Due to high correlation coefficients between the study's mass deposition model, it is difficult to conclude what correlations are seen in multivariate analysis regarding respiratory symptoms and time spent cooking. A quite high correlation coefficient was noted between fever and respiratory symptoms, while it still showed statistically significant correlation and elevated OR in the logistic regression, the previously seen correlations noted for the mass deposition model and smokers in the household with respiratory symptoms, were not noticed in this analysis, causing unclarities in what multivariate analysis is most likely to reflect the actual real-life correlations. Furthermore, the subgroups for charcoal, wood, and dung, vary greatly in size, with numbers of 8, 1,730, and 24 questionnaire answers, respectively. This could also influence the statistical analysis, and makes a multivariate analysis less precise, due to limit input data causing difficulties in assessing statistical significance in multivariate analysis, resulting that the statistical analysis regarding dung and especially charcoal can be argued. Regarding correlation between respiratory symptoms and usage of certain fuel types, a statistically significant result was still noticed, showing increased OR for animal dung compared to wood. Although, it is worth noticing that all the fuels being used in this cohort are highly polluting fuels, making the resulting statistical analysis a comparison between different health hazardous fuel types. With this in thought, it would be interesting to find a baseline subgroup in the same region using less polluting cooking practices, e.g., electrical stoves, to gain more insights in the health hazards of all these biomass fuels. A cohort with more individuals being represented in each fuel type usage group would be a good step forward in future analysis of this setting. Additionally, several households were excluded due to them using fuel types, such as kerosene, where combustion experiment data was not available. By performing more combustion experiments, for more fuel types, a wider study population would be available, offering an even more interesting analysis, for more combustion events.

Contemplating the study aims and research questions, the model has further developed the modelling aspects to determine the deposition resulting from IAP in LICs settings, however, additional efforts

are needed before the model is ready for usage. Study aim 1 (Develop a model, that requires only the limited amount of input variables normally available in LIC studies, to estimate the deposited mass in the respiratory tract arising from cooking-related biomass combustion exposure), has been met, while further improvement possibilities both regarding the assumptions for the model and the amount of in-data used to achieve the normalised mass size distribution curves. Study aim 2 (Describe a generalisable approach to use model for different demographics, allowing for analysis of different demographic groups), has also been met, since the model is adaptable for different populations, by changing the assumed respiratory-associated parameters, as well as noticing several interesting aspects to further investigate regarding, e.g., DF calculation for certain health ailments and/or age groups. Study aim 3 (Use the model to estimate the deposited mass of PM in a subset of the cohort population of the Haramaya district in Ethiopia) has also been met, where the estimated deposition has been calculated and further analysed, showing statistically significant differences depending on fuel type being used, as well as difference in ultrafine PM deposition depending on fuel type usage, which is a part of study aim 4 (Investigate if noticeable differences between fuel type usage groups can be seen in the resulting estimated mass deposition from the model), thereby making that study aim met as well. Study aim 5 (Conduct an initial test of the model by investigating potential associations between adverse health outcomes and the estimated deposited dose), has also been met, where the result was contrary to the hypothesis, but can be explained due to several different factors, indicating that further preparations (regarding, e.g., modelling assumptions, health data, and combustion experiments used as in-data) are needed before the model can be implemented in that setting.

Reflecting on the study questions, number 1 (Can the aerosol deposition models found in literature be adapted to describe the deposited mass of PM arising from biomass combustion for IAP estimation in LICs?), can be answered by yes, while it is highly dependent on the assumptions made for and input data for the deposition model. Therefore, it seems that deposition can be modelled, but it has to be done with careful consideration regarding the situation that the model is trying to estimate, with consideration for which assumptions can be made and which parameters that can be gathered for the households with precision. Regarding study question 2 (What findings are seen when implementing the model, developed by combining in-lab combustion experiments of PM [using ventilation details from on-site in-house measurements] with a cohort population, practicing the combustion activities of interest?), it can be shown that clear differences between fuel type usage can be noticed, and that all groups are exposed to more PM than the WHO guidelines for PM2.5 24 hour average exposure. Moving on to study question 3 (Are the findings from implementing the model in-line with the previous findings in the area and can differences in mass deposition be seen in the population?), we conclude that the findings show deposition indicating a higher level of exposure than what is recommended, which is what previous studies in low-income settings has shown (84, 85).The model show that both PM mass and number depositions can be estimated, however, the epidemiological analysis show results contrary to the broader analytical studies previous noted in literature, probably due to several factors associated with number of combustion experiments used as in-data, precision of health data reported in the cohort questionnaire, cohort population size, and modelling parameter assumptions. Study question 4 (Can the developed model show a difference between deposited mass of PM from cooking activities using biomass-combustion depending on fuel type usage?) is also answered, since clear differences can be seen for the different fuel types being used, according to the ANOVA results presented in this thesis. Finally, for study question 5 (Is there a correlation between deposited mass of PM from cooking activities using biomass-combustion and adverse health effects of residents of the study population?), there has been correlations noticed. Some were uncontroversial, e.g., that smokers in the household show correlations with the health outcome of interest, while others

are more unclear, i.e., the slightly reduced OR of the mass deposition estimate and the health outcome of interest, which persisted for multivariate analysis as well. The question can be answered with more studies and considerations are necessary, both regarding the model (with assumptions and input data showing possibilities of improvement) and the cohort (with health data precision and cohort size).

7. Conclusion

This study highlights the need of further studies regarding IAP exposure, deposition, and its corresponding health effects, in low-income settings. The developed model is able to estimate particle mass and number depositions in the human respiratory tract, with possibilities for focusing on region-specific deposition. While certain correlations were noticed between mass depositions and adverse health outcomes, further studies are required to gain additional clarity in this area. The model can describe the deposition of PM caused by biomass-combustion related to household activities and is possible to further improve when new combustion data is generated.

The guidelines described by the WHO regarding air pollution exposure are not tangible for low-income settings, where this study indicate breach of guideline levels after mere minutes of exposure. In an attempt to precise the levels of deposition, this model may be part of a more concrete estimate, which, in turn, may be used for a more informed knowledge regarding IAQ and IAP exposure for policy making in low-income settings. Air pollution is a growing issue, affecting all of us, and hopefully, this thesis will contribute to further insights in this vital area of science.

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