Evaluating two tools used to predict workplace chemical exposures: the IHMOD 2.0 and the SDM 2.0

May 17, 2021

Word count: 4,200

Introduction

Industrial hygiene involves the study and control of workplace hazards that may result in illness. Industrial hygienists are faced with the arduous task of evaluating contaminant exposures in the workplace. These exposure estimates are essential for the proper functioning of many industrial processes. For instance, exposure assessments determine whether exposures to chemical, physical, or biological agents are acceptable and whether any further steps, including worker training and implementation of improved ventilation systems, must be taken (Mulhausen & Damiano, 2006, p. 3; Arnold Et al., 2016, p. 2). The resulting insights into the health and safety risks associated with performing work tasks in these environments dictate whether or not federal and agency regulations are met and if these activities can safely continue under their current conditions.

The field of industrial (or occupational) hygiene, however, has become increasingly difficult in recent years. Namely, providing accurate and precise exposure assessments is more challenging than ever. Today's workplace is becoming more complex; with the increasing diversification of industrial processes in recent decades, the variety of chemical, physical, and biological agents that workers are exposed to has gotten harder to predict and analyze (Mulhausen & Damiano, 2006, p. 4). Industrial hygienists must spend hours, and sometimes days, collecting information about chemical agents and the associated health effects, workforce information, existing protective equipment, and many more variables that factor into their evaluations (Mulhausen & Damiano, 2006, p. 5-7; Arnold Et al., 2016, p.2; Mulhausen Et al., 2006, p. 1). Industrial hygienists are also held more accountable for the accuracy of their evaluations. The organizations they serve answer to many more stakeholders than in the past, including employees, customers, regulators, the press, and the communities in which they operate (Mulhausen & Damiano, 2006, p. 3).

In concert with all of these external challenges that hygienists face, internal difficulties present another issue. One factor is something called an unconscious cognitive bias, which can be common when decisions must be made with incomplete data and there is inherent uncertainty. This phenomenon is associated with the part of the brain where decision making is processed. The Prefrontal Cortex (PFC) is easily distracted by stimuli that have a disproportionate impact on decision-making, which explains the inaccuracy and inconsistency of subjective intuitive decisions (Arnold Et al., 2016, p. 2-3; Arnold Et al., 2006, p. 6). Thus, regardless of an assessor's years of experience or professional credentials, his or her subjective judgment is more likely to be incorrect. These cognitive errors, combined with inadequate training, sometimes lead hygienists to misinterpret exposures that are often represented by skewed lognormal distributions

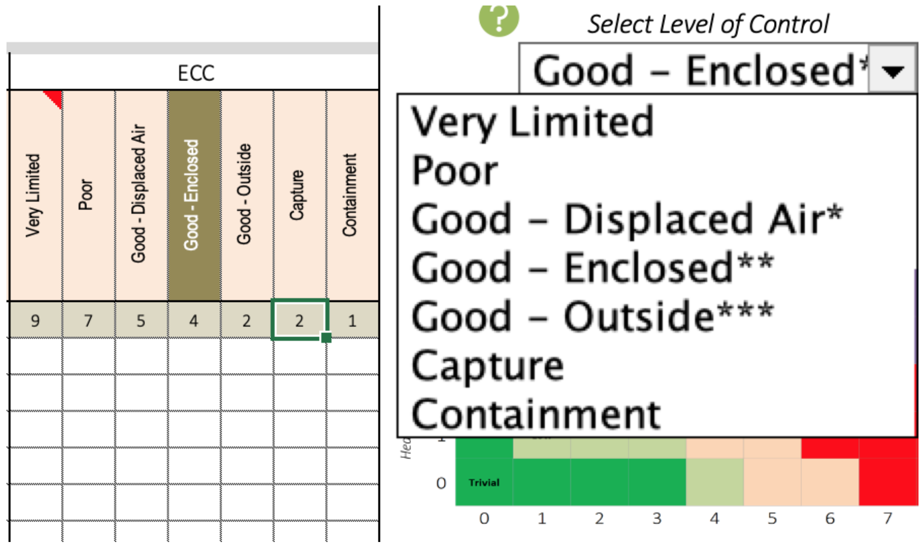
Despite the training necessary to become a Certified Industrial Hygienist (CIH), professional credentials granted by the American Board of Industrial Hygiene, education alone simply cannot prepare someone for the plethora of unpredictable situations he or she will encounter. Real world situations rarely conform to textbook descriptions of variables like the efficacy of ventilation systems, the heterogeneity of workers, and consistent chemical generation rates. An industrial hygienist may be overwhelmed by the large number of stimuli. Accordingly, a pattern that has emerged in recent years is the need for more advanced strategies to aid industrial hygienists in providing workplace exposure assessments. Studies have shown that objective, structured approaches facilitated by predefined algorithms are more resistant to the aforementioned cognitive biases that hygienists face (Arnold Et al., 2016, p. 3; Arnold Et al., 2006, p. 7). This is because they can filter out nonessential information and focus the user on the most critical variables and inputs for their decision-making process. Additionally, these tools ensure that information is processed in a consistent order. One such tool is the checklist-centered Structured Deterministic Model (SDM), which guides the application of several heuristics, based on qualitative observations, to arrive at an approximate exposure control category (ECC). ECCs are defined as fractions of the Occupational Exposure Limit (OEL), based on the 95th percentile value of an exposure profile. These fractions are shown in Figure I. Categorical ranges differ based on the type of contaminant: volatile and semi-volatile chemicals utilize an expanded 10 category framework, while only the first four categories are used for fibers, particulates, and aerosols.

Figure I. This table displays the ranges of the ratio between contaminant concentration and OEL for each of the nine ECCs. For instance, a scenario with a workplace concentration of 400 parts per million and an OEL of 200 parts per million would yield a ratio of 2 and be considered a category 5 exposure (exposures are rounded to the higher ECC if it's on the border between two categories).

Cat	Min	Max	Exposure Control Category (ECC)
0	0	0.1	less than 0,01
1	0.1	0.1	0,01 to 0,1
2	0.1	0.5	0,1 to 0,5
3	0.5	1	0,5 to 1
4	1	2	1 to 2
5	2	5	2 to 5
6	5	10	5 to 10
7	10	25	10 to 25
8	25	50	25 to 50
9	50	1000000	more than 50

Heuristics are simple rules used by hygienists to simplify problem solving. ECC's, rather than providing a precise concentration of chemical exposures, are broader categories that determine what type of actions must be taken to address worker safety concerns. The SDM 2.0 (the newest version will be used in this study) is designed to be user friendly and therefore requires relatively few inputs. The foundation of the SDM is based on several well-known principles within the field, including the relationship between ventilation level and the maximum airborne concentration of a volatile chemical, how temperature affects vapor pressure, and occupational exposure limits (Arnold Et al., 2016, p. 3-4; Stenzel & Arnold, 2006, p. 3-7). One of the most critical inputs is the level of control, which indicates the steps that are already being taken to minimize exposures to contaminants in a specific workplace. The SDM contains a dropdown menu, as seen in Figure II, from which the user can select the closest approximation to the level of control reflected in the setting. This selection is the prime determinant of the estimated ECC.

Figure II. SDM 2.0 Report Page. The dropdown menu with the different options for the level of control is seen on the right side of the image. The resulting predictions for the ECC based on the selected level of control are seen on the left side of the image. Clearly, the selected level of control can yield a wide range of predicted ECCs.



Most industrial hygienists are already familiar with these relationships and may have limited experience applying them to certain complicated situations in a systematic way. Thus, this tool serves as more of an extension to an industrial hygienist's inherent capabilities, rather than as a completely new invention using the most pioneering equations in the field. Another tool that has gained popularity in recent years is mathematical modeling. Modeling has several advantages over sampling. Firstly, it typically costs far less time and money than traditional sampling methods due to its independence from actual air sampling (Nicas, 2006, p. 1). This non-reliance on air sampling means that modeling is extremely versatile and can evaluate exposures from discontinued industrial practices, as well as future proposed practices. Secondly, mathematical modeling can be applied as a probabilistic tool and generates confidence intervals of likely exposure levels, thus providing a more nuanced exposure estimate that more accurately reflects the variability of real-world conditions (Nicas, 2006, p. 1; Arnold Et al., 2017, p. 3). These confidence intervals are generated with a few inputs, the most common being the chemical generation rate, the ventilation rate and random air velocity, and the room volume (Nicas, 2006, p. 5-6; Arnold Et al., 2017, p. 9-11; Arnold Et al., 2017. p. 3-4). Models have the additional advantage of being customized to fit certain types of environments. For instance, one commonly used model is designed to replicate a room in which there are two "zones" of exposure: a "near-field" that encompasses a worker's immediate breathing zone and a "far-field" that contains the rest of the room (Nicas, 2006, p. 5; Gaffney Et al., 2008, p. 3; Nicas & Neuhaus, 2008, p. 4). Thus, while the SDM delivers a high level of accessibility in various situations, mathematical models may provide greater assessment accuracy in scenarios for which they are designed to replicate.

Both the SDM and mathematical models have gained increasing popularity in recent years as the demand for structured, objective exposure assessments has increased. These two tools have also shown consistent success in providing accurate exposure estimates through highly controlled laboratory studies, as well as anecdotal evidence from the field. However, there is little experimental evidence comparing the performance of these two tools. Additionally, as the Checklist is a relatively new tool, there is very limited literature on the efficacy of the SDM 2.0 and its ability to predict workplace exposures in certain situations, such as those involving chemical mixtures. Thus, this study seeks to provide a systematic evaluation of these two tools' relative accuracy and compare the situations for which they are most suited. Case studies from numerous industrial processes will be compiled and inputted into each of these two types of tools, with subsequent statistical analysis showing agreement and any discrepancies in their results.

Methods

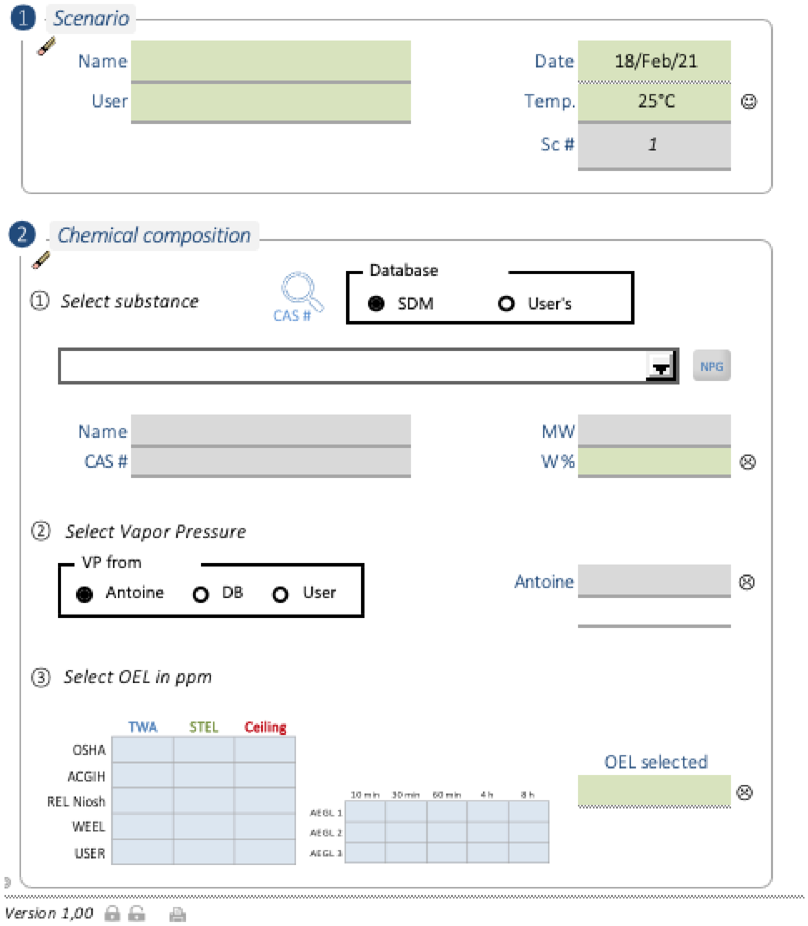
Case studies involving a wide range of industrial processes were compiled from other studies evaluating similar tools used to aid industrial hygienists. Because the mathematical modelling tool used in this study requires more comprehensive inputs than the SDM, studies evaluating other mathematical models were selected in order to increase confidence that the necessary information was present. Inputs for both tools can be found in Table I. Steps specific to each tool are described in further detail below.

The Structured Deterministic Model

The SDM has two settings, each for a different "checklist": the first checklist is for assessing pure, relatively pure agents, or chemicals contained in mixtures composed of volatile and semi-volatile agents. The other checklist is for assessing particulates, fibers, and aerosols. The case studies were divided accordingly; Scenarios 1, 2, 3, 4, 7, and 8 were evaluated using the first checklist, while scenarios 5, 6, and 9 were evaluated using the second checklist.

Required inputs for the vapor-based checklist include the following: the name of the contaminant, the weight percent (relative purity) of the substance, the workplace temperature, the contaminent's vapor pressure, and the desired occupational exposure limit (OEL). Figure III shows an image of what the user sees.

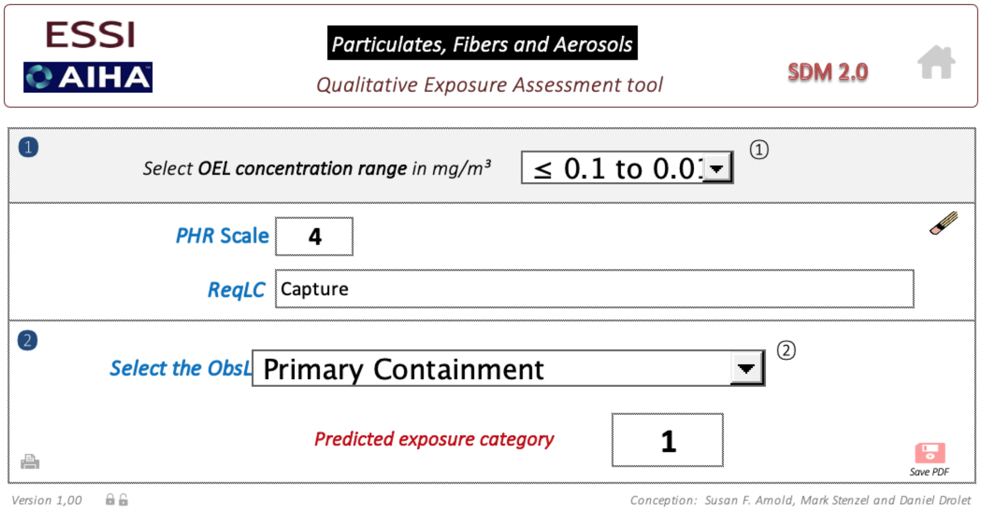
Figure III. A Partial View of the SDM 2.0 Input Screen



Once all the inputs are entered and the tool deems the values satisfactory, the user may then send the data to analysis. After the user selects the appropriate level of control from the dropdown menu seen in Figure II from the report page, the SDM outputs the predicted ECC.

The particulates, fibers, and aerosols checklist is even more streamlined than the first, requiring only two inputs: an OEL concentration range and the observed level of control. This is because contaminants in this category behave similarly, so the SDM does not need very much information to generate a satisfactory assessment of the workplace exposure. Figure IV shows an image of what the user sees.

Figure IV. The user inputs only two pieces of information: an OEL concentration range and the observed level of control. The SDM uses this information to estimate the PHR scale and the required level of control.

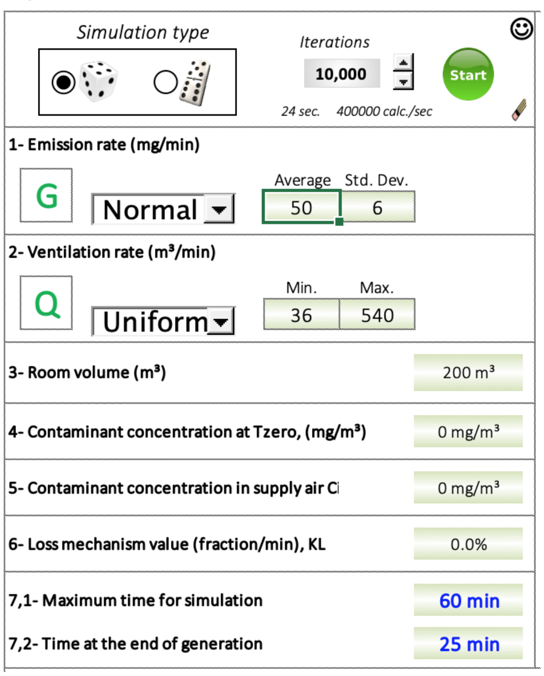


Upon providing these two key pieces of information, the user can see the predicted ECC at the bottom of the screen.

The IHMOD 2.0

The particular mathematical modelling tool used in this study is called the IHMOD, which contains models designed for many different situations. All scenarios here were evaluated with one version of the Well-Mixed Room (WMR) model and one version of the Near Field-Far Field (NF-FF) model. Scenario 2 was assessed using the WMR and NF-FF models for decreasing emission rates. The remaining scenarios were assessed using the WMR and NF-FF models for constant emission rates. The required values for the WMR model (constant emission) are shown in Figure V. The NF-FF model for constant emissions uses the same inputs, but with additional information regarding the sizes of the two zones and the airflow rate between them. The WMR and NF-FF models for decreasing emission rates, along with the values used in the models with constant emission rates, require initial contaminant masses and evaporation rates.

Figure V. The WMR model for constant emission rates.



The mathematical models output their results in the form of confidence intervals for the concentrations measured in milligrams per cubic meter. This study, in accordance with standard usage of the tool, takes the 95th percentile of outputs to increase confidence that the true exposure level was captured. In order to facilitate comparison between the SDM and IHMOD 2.0 (the newest version will be used in this study), these results were categorized into ECCs through the following process: the predicted concentrations were converted to parts per million, then divided by the contaminant's OEL. This ratio between the workplace concentration and the concentration limit was grouped into the appropriate ECC according to the ranges displayed in Figure I.

Special Cases

If industrial hygienists aren't careful to take into account scenario-specific information, they may use the IHMOD incorrectly and arrive at an inaccurate exposure prediction. The inputs for the IHMOD assume near-uniform exposure for the entire time period entered. In some cases, however, workers may be exposed to different levels of contamination based on his or her location in the room. This might occur if the worker isn't performing the indicated task for the entire shift. To accommodate for these irregular exposures, the predicted concentration from the IHMOD was multiplied by the fraction of the entire workday that the worker was actually being exposed to the contaminant. This situation applied to scenarios 3 and 9.

Table I

Exposure scenario #	Source	Chemical agent	Work task + extra info	SDM 2.0 inputs	IHMOD 2.0 well-mixed room model inputs	IHMOD 2.0 near-field far-field model inputs
1	Gaffney Et al.	Methanol	Cleaning semiconductor wafers; day 1 of study; worker personal exposure	Substance: Methyl alcohol Temperature: 17.9℃ Weight percent: >99% Vapor pressure: 96 mmHg at room temperature (Antoine's) OEL: 200 ppm (OSHA TWA) Level of Control: Good - Enclosed	Emission rate, G: - Generation rate: 588 milligrams per minute Ventilation rate, Q: - 16.2 cubic meters per minute (10 air changes per hour?) Room volume, V: - 102 cubic meters Time: - Exposure duration: 4 hours	Emission rate, G: - Generation rate: 588 milligrams per minute Ventilation rate, Q: - 16.2 cubic meters per minute Random air velocity, S: - Velocity: 3.6 meters per minute - FSA: 6.28 square meters - Interzonal air flow rate, β: 11.3 cubic

						meters per minute Room volume, V: - Total room volume: 102 cubic meters - Near-field volume: 2.1-cubic meters - Near-field shape: hemisphere with radius of 1 meter - Far field volume: 99.9 cubic meters Time: - Exposure duration: 4 hours
2	Nicas Et al.	Benzene	Loosening rusted nuts and bolts with liquid benzene; combination 4, replicate 1, 15 min TWA	Substance: Benzene Temperature: 25 ℃ Weight percent: 27.3% Vapor pressure: 95.1 mmHg at 25 ℃. OEL: 5 ppm (OSHA STEL) Level of Control: capture	Initial liquid mass: - Mass of benzene applied at the start: 2323 milligrams Evaporation rate constant, ($\alpha\alpha$): - $\alpha\alpha\alpha$= 0.139 min^{-1} Ventilation rate, Q: - 0.264 cubic meters per minute Room volume, V: - 136 cubic meters Time: - Exposure	Initial liquid mass: - Mass of benzene applied at the start: 2323 milligrams Evaporation rate constant, ($\alpha\alpha\alpha$): - $\alpha\alpha\alpha$= 0.139 min^{-1} Ventilation rate, Q: - 15.9 cubic meters per hour Random air velocity, S: - Velocity: 15.2 meters per

					duration: 15 minutes	minute - FSA: 3.32 square meters - Interzonal air flow rate, β: 25.2 cubic meters per minute Room volume, V: - Total room volume: 136 cubic meters - Near-field volume: 0.5 cubic meters - Near-field shape: rectangular box - Far-field volume: 135. Time: - Exposure duration: 15 minutes
3	Arnold Et al.	Acetone	Giving waterless manicures using acetone to clean nail surfaces	Substance: Acetone Temperature: 25 ℃ Weight percent: 100% Vapor pressure: 225 mmHg at 25 ℃. OEL: 250 parts per million (ACGIH 8 hour TWA)	Emission rate, G: - Average generation rate: 21 milligrams per minute - Lognormal distribution with inputs (16.3, 2.68) Ventilation rate, Q: - Uniform distribution with a minimum of 6.2 cubic meters per minute and	Emission rate, G: - Average generation rate: 21 milligrams per minute - Lognormal distribution with a geometric mean of 16.3 milligrams per minute and a geometric standard deviation of

				Level of Control: Good Enclosed/Containment 11.5 air turnovers per hour	a maximum of 7.7 cubic meters per minute Room volume, V: - Total room volume: 31 cubic meters Time: - Average time for a manicure: 35 minutes	2.68 milligrams per minute Ventilation rate, Q: - Uniform distribution with a minimum of 6.2 cubic meters per minute and a maximum of 7.7 cubic meters per minute Random air velocity, S: - Velocity: 15 meters per minute - FSA: 3.08 square meters - Interzonal air flow rate, β: Lognormal distribution with geometric mean of 23.1 milligrams per minute and a geometric standard deviation of 1.1 milligrams per minute Room volume, V: - Total room volume: 31 cubic meters - Near-field

						volume: 1.0 cubic meters - Near-field shape: hemisphere with radius of 0.782 meters - Far-field volume: 29.9 cubic meters Time: - Average time for a manicure: 35 minutes - 5 manicures over 8 hours
4	Arnold Et al.	Methylene Chloride	Collecting a liquid sample from a manufacturing vessel	Substance: methylene chloride Temperature: 25 ℃ Weight percent: 100% Vapor pressure: 435 mmHg at 25 ℃. OEL: 125 ppm (OSHA STEL) Level of Control: Good - Outside Air	Emission rate, G: - Lognormal distribution with a geometric mean of 220 milligrams per minute and a geometric standard deviation of 4 milligrams per minute Ventilation rate, Q: - Uniform distribution with a minimum of 94 cubic meters per minute and a maximum	Emission rate, G: - Lognormal distribution with a geometric mean of 220 milligrams per minute and a geometric standard deviation of 4 milligrams per minute Ventilation rate, Q: - Uniform distribution with a minimum of 94 cubic meters per minute and a maximum

						of 140 cubic meters per minute Room volume, V: - Total room volume: 379 cubic meters Time: - Exposure duration: approximately 15 minutes	of 140 cubic meters per minute Random air velocity, S: - Velocity: between 1.8 and 3.5 meters per minute - FSA: 4.02 square meters - Interzonal air flow rate, β: uniform distribution with a minimum of 3.5 cubic meters per minute and a maximum of 7.1 cubic meters per minute Room volume, V: - Total room volume: 379 cubic meters - Near-field volume: 1.1 cubic meters - Near-field shape: hemisphere with radius of 0.8 meters - Far-field volume 378.3 cubic meters Time: - Exposure

						duration: approximately 15 minutes
5	Arnold Et al.	Silica	Removing iron parts from sand molds in an iron foundry	OEL concentration range in milligrams per cubic meter: 0.025 (ACGIH 8 hour TWA) ObsLC: General ventilation (2 - 4 air turnovers/hr	Emission rate, G: - Lognormal distribution with a geometric mean of 43.7 milligrams per minute and a geometric standard deviation of 2.64 milligrams per minute Ventilation rate, Q: - Uniform distribution with a minimum of 80 cubic meters per minute and a maximum of 100 cubic meters per minute Room volume, V: - Total room volume: 1200 cubic meters Time: - Exposure duration: 8 hours	Emission rate, G: - Lognormal distribution with a geometric mean of 43.7 milligrams per minute and a geometric standard deviation of 2.64 milligrams per minute Ventilation rate, Q: - Uniform distribution with a minimum of 80 cubic meters per minute and a maximum of 100 cubic meters per minute Random air velocity, S: - Velocity: 18.9 meters per minute - FSA: 3.6 square meters - Interzonal air flow rate, β: Lognormal distribution with

						geometric mean of 34 milligrams per minute and a geometric standard deviation of 1.5 milligrams per minute Room volume, V: - Total room volume: 1200 cubic meters - Near-field volume: 1.1 cubic meters - Near-field shape: hemisphere with radius of 0.807 meters - Far-field volume: 1199 cubic meters Time: - Exposure duration: 8 hours
6	Arnold Et al.	Lithium Cobalt Oxide	Mixing and cleaning in a clean room environment	OEL concentration range in milligrams per cubic meter: 0.02 (ACGIH 8 hour TWA) ObsLC: General Ventilation	Emission rate, G: - Uniform distribution with a minimum of 0.03 milligrams per minute and a maximum of 0.06 milligrams per minute	Emission rate, G: - Uniform distribution with a minimum of 0.03 milligrams per minute and a maximum of 0.06 milligrams per minute

					Ventilation rate, Q: - Uniform distribution with a minimum of 2.68 cubic meters per minute and a maximum of 4.02 cubic meters per minute Room volume, V: - Total room volume: 126 cubic meters Time: - Exposure duration: 8 hours	Ventilation rate, Q: - Uniform distribution with a minimum of 2.68 cubic meters per minute and a maximum of 4.02 cubic meters per minute Random air velocity, S: - Velocity: 3.9 meters per minute - FSA: 4.0 square meters - Interzonal air flow rate, β: Lognormal distribution with geometric mean of 7.8 milligrams per minute and a geometric standard deviation of 2.1 cubic meters per minute Room volume, V: - Total room volume: 126 cubic meters - Near-field

						volume: 1.1 cubic meters - Near-field shape: hemisphere with radius of 0.807 meters - Far-field volume: 124.5 cubic meters Time: - Exposure duration: 8 hours
7	Robbins Et al.	Benzene	Using a small cloth to wipe a metal paint tray with toluene spiked with 0.1% benzene; short-term exposure; 10mL Toluene with 0.1% Benzene	Substance: benzene Temperature: approximately 16.9℃ Weight percent: 0.0015% OEL: 5.0 parts per million (15 minute short term exposure limit (OSHA STEL)) Toluene: 200 ppm (OSHA TWA) Level of Control: Poor	Emission rate, G: - Average generation rate: 0.8765 milligrams per minute Ventilation rate, Q: - 0.286 cubic meters per minute Room volume, V: - Total room volume: 40.1 cubic meters Time: - Exposure duration: 15 minutes	Emission rate, G: - Average generation rate: 0.8765 milligrams per minute Ventilation rate, Q: - 0.286 cubic meters per minute Random air velocity, S: - Velocity: 3.75 meters per minute - FSA: 1.3 square meters - Interzonal air flow rate, β: 2.46 cubic meters per minute Room volume, V: - Total room volume: 40.1 cubic

						meters - Near-field volume: 0.2 cubic meters - Near-field shape: hemisphere with radius of 0.4572 meters - Far-field volume: 39.9 Time: - Exposure duration: 15 minutes
8	Robbins Et al.	Benzene	Using a small cloth to wipe a metal paint tray with toluene spiked with 0.1% benzene; short-term exposure; 50mL Toluene with 0.1% Benzene	Substance: benzene Temperature: approximately 16.9℃ Weight percent: 0.0015% OEL: 5.0 parts per million (15 minute short term exposure limit (OSHA STEL)) Toluene: 200 ppm (OSHA TWA) Level of Control: Poor	Emission rate, G: - Average generation rate: 2.92 milligrams per minute Ventilation rate, Q: - 0.286 cubic meters per minute Room volume, V: - Total room volume: 40.1 cubic meters Time: - Exposure duration: 15 minutes	Emission rate, G: - Average generation rate: 2.92 milligrams per minute Ventilation rate, Q: - 0.286 cubic meters per minute Random air velocity, S: - Velocity: 3.75 meters per minute - FSA: 1.3 square meters - Interzonal air flow rate, β: 2.46 cubic meters per minute Room volume, V: - Total room volume: 40.1 cubic meters

						- Near-field volume: 0.2 cubic meters - Near-field shape: hemisphere with radius of 0.4572 meters - Far-field volume: 39.9 Time: - Exposure duration: 15 minutes
9	Hofstetter Et al.	Toluene	Application of a toluene-containing spray paint to a surface	Setting: Particulates, Fibers, and Aerosols OEL concentration range in milligrams per cubic meter: OEL: 150 ppm (NIOSH STEL) = 127 mg/m^3 ObsLC: poor Weight percent: 16% Vapor pressure: 22 mmHg	Emission rate, G: - Average generation rate: 13,600 milligrams per minute Ventilation rate, Q: - 3.9 cubic meters per minute Room volume, V: - Total room volume: 77.7 cubic meters Time: - Generation time: 4 minutes - Exposure duration: 15 minutes	Emission rate, G: - Average generation rate: 13,600 milligrams per minute Ventilation rate, Q: - 3.9 cubic meters per minute Random air velocity, S: - Velocity: 9 meters per minute - FSA: 20 square meters - Interzonal air flow rate, β: 90 cubic meters per minute Room volume, V: - Total room volume: 77.7 cubic meters - Near-field

						volume: 8 cubic meters - Near-field shape: cube - Far-field volume: 69.7 cubic meters Time: - Generation time: 4 minutes - Exposure duration: 15 minutes
10	Arnold Et al.	2-Butanone	2-Butanone delivery volume (medium, test number location 150.1) of 0.1 milliliters per minute in a controlled laboratory setting	Substance: 2-Butanone Temperature: approximately 25.0℃ Weight percent: 80.5% Vapor pressure: 71 mmHg OEL: 200ppm (OSHA PEL) Level of Control: good - enclosed	Emission rate, G: - Average generation rate: 80.5 milligrams per minute Ventilation rate, Q: - 0.299 cubic meters per minute Room volume, V: - Total room volume: 11.76 cubic meters Time: - Exposure duration: 120 minutes	Emission rate, G: - Average generation rate: 80.5 milligrams per minute Ventilation rate, Q: - 0.299 cubic meters per minute Random air velocity, S: - Velocity: 1.10 meters per second - FSA: 1.34 square meters - Interzonal air flow rate, β: an average of 0.74 cubic meters per minute Room volume, V: - Total room volume: 11.76 cubic meters - Near-field

						volume: 0.105 cubic meters - Near-field shape: cube - Far-field volume: 11.79 cubic meters Time: - Exposure duration: 120 minutes

Results

The values from Table I were inputted into the SDM 2.0 and the IHMOD 2.0 Well-Mixed Room (WMR) and Near Field Far Field (NF-FF) models to obtain predicted exposure levels for each scenario. The predicted concentrations (contaminant mass) of contaminants from the ten case studies are shown in Table II, as well as the ratios between outputs from the different tools. It should be noted here that the SDM 2.0 does not predict a mass concentration value for aerosols, fibers, or particulates. Scenarios 5, 6, and 9 are part of this group of chemicals and thus do not have predicted mass concentrations. Table III shows these same results in the form of Exposure Control Categories (ECC). The SDM 2.0 directly outputs predicted ECCs. Meanwhile, the IHMOD 2.0 WMR and NF-FF models output concentrations representing the 95th percentile of exposures that are then converted to ECCs by dividing the concentrations by their associated OELs. Those ratios are then matched up to the corresponding category according to Table IV. Table III also reports the deviation of these results from the measured ECCs, as well as from each other. Lastly, Figure VI displays these categorical discrepancies in a more visual format.

Table II. Outputs from the SDM and IHMOD tools for the 10 scenarios are displayed here, along with ratios between the predictions from different tools.

Scenario	SDM 2.0 Predicted Concentration	IHMOD WMR Predicted Concentration	IHMOD NF-FF Predicted Concentration	Personal Exposure Measurement Concentration	Ratio SDM 2.0/ Personal Exposure Measurement Concentration	Ratio WMR/Personal Exposure Measurement Concentration	Ratio NF-FF/Personal Exposure Measurement Concentration	Ratio SDM/WMR	Ratio SDM/NF-FF	Ratio WMR/NF-FF
1	113 ppm	26.9 ppm	66.1 ppm	73.0 ppm	1.55	0.368	0.905	4.20	1.71	0.407
2	12.5 ppm	10.5 ppm	16.4 ppm	10.6 ppm	1.18	0.99	1.55	1.19	0.762	0.64

3	3.03 ppm	1.49 ppm	1.93 ppm	1.50 ppm	2.02	0.993	1.29	2.03	1.57	0.772
4	190 ppm	4.26 ppm	116 ppm	141.3 ppm	1.34	0.03	0.821	44.6	1.64	0.0367
5	N/A	2.26 mg/m^3	7.75 mg/m^3	0.16 mg/m^3	N/A	14.1	48.4	N/A	N/A	0.292
6	N/A	0.271 mg/m^3	0.390 mg/m^3	0.04 mg/m^3	N/A	6.78	9.75	N/A	N/A	0.695
7	a*-0.01 ppm b*-249 ppm	0.0419 ppm	0.135 ppm	0.135 ppm	1840	0.31	1.00	5940	1840	0.310
8	a-0.01 ppm b-249 ppm	0.140 ppm	0.448 ppm	0.385 ppm	647	0.364	1.16	1780	556	0.313
9	N/A	118 mg/m^3	127 mg/m^3	99.55 mg/m^3	N/A	1.19	1.28	N/A	N/A	0.929
10	115 ppm	99.4 ppm	98.9 ppm	67.73 ppm	1.70	1.47	1.46	1.16	1.16	1.01

*a: benzene, b: mixture

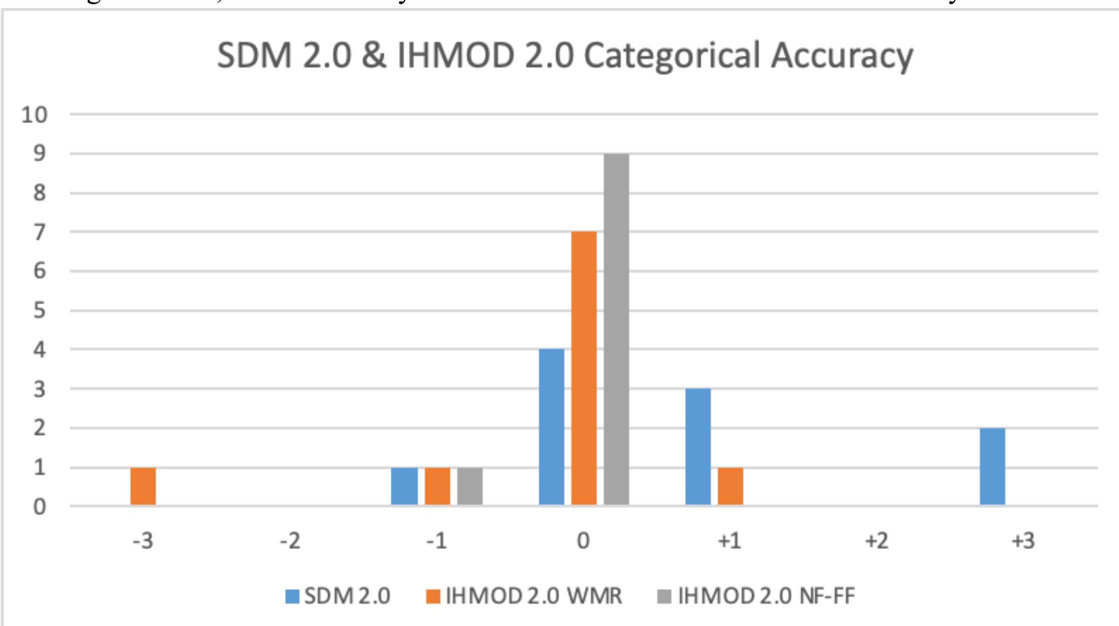
Table III. Categorical outputs and relevant comparisons between tools, using data converted from Table II.

Scenario	SDM 2.0 Predicted ECC	IHMOD WMR Predicted ECC	IHMOD NF-FF Predicted ECC	Personal Exposure Measured ECC	Categorical Difference Between SDM and Measured	Categorical Difference Between WMR and Measured	Categorical Difference Between NF-FF and Measured	Categorical Difference Between SDM and WMR	Categorical Difference Between SDM and NF-FF	Categorical Difference Between WMR and NF-FF
1	3	2	2	2	1	0	0	1	1	0
2	5	5	5	5	0	0	0	0	0	0
3	1	0	0	0	1	0	0	1	1	0
4	4	1	3	4	0	3	1	3	1	2
5	4	4	4	4	0	0	0	0	0	0
6	4	4	4	4	0	0	0	0	0	0
7	a*:0	0	1	1	3	1	0	4	3	1

	b*:4									
8	a:0 b:4	1	1	1	3	0	0	3	3	0
9	2	4	3	3	1	1	0	2	1	1
10	3	2	2	2	1	0	0	1	1	0

*a: benzene, b: mixture

Figure VI. All three tools exhibited fairly strong agreement with the actual measured conditions. As seen in the figure below, there were only three instances where a tool was inaccurate by more than one ECC.



As previously mentioned, the ratio between the concentrations predicted by each of the tools and the measured exposure were calculated for each scenario. This was done to show how strong the agreement was between each tool's prediction and the actual exposure. The SDM 2.0's predicted concentration was within a factor of two for four out of eight scenarios. Meanwhile, the predicted concentrations from the IHMOD 2.0 showed stronger agreement with the measured exposure. Both the WMR and NF-FF model's predictions were within a factor of two for eight out of the ten scenarios. The SDM overestimated the exposure concentration for all seven of the scenarios for which it provided an output. The SDM 2.0 correctly estimated the ECC for 4/10 of the scenarios, overestimated the ECC for 5/10 of the scenarios, and underestimated the ECC for 1/10 of the scenarios. Of the scenarios where the SDM 2.0 predicted the incorrect ECC, it was off by one category for four of the scenarios and off by three or more categories for two of the scenarios. The IHMOD 2.0 WMR model overestimated the ECC for 1/10 of the scenarios, correctly estimated the ECC for 7/10 of the scenarios, and underestimated the ECC for 2/10 of the scenarios. Of the scenarios where the IHMOD WMR model predicted the incorrect ECC, it was off by one category for two of the scenarios and off by three or more categories for one of the scenarios. The IHMOD 2.0 NF-FF overestimated the ECC for 0/10 of the scenarios, correctly estimated the ECC for 9/10 of the scenarios, and underestimated the ECC for 1/10 of the scenarios. For the scenario where the

IHMOD NF-FF model predicted the incorrect ECC, it was off by one category.Overall, the NF-FF model proved to be the most accurate tool for predicting the correct ECC. The SDM 2.0 was the least effective. The Checklist and both mathematical models showed perfect agreement with the measured ECC for the two scenarios involving particulates.

Discussion

There were several notable observations made from the results. Firstly, both the WMR and NF-FF models were more precise in their estimates than the SDM. This may be explained by the fact that the SDM requires the least amount of scenario specific information. This means that the Checklist can only provide a rough estimate, and its assessment is not designed to reflect the intricacies of individual facilities. There is a tradeoff between ease of use and precision. The mathematical models were also more accurate than the SDM with regard to ECC. The same factors discussed previously contributed to this fact. The SDM, as seen in Figure VI, gave a larger spread of results, but the vast majority were still within one ECC from the measured. The models were considered to have worked well if it predicted the exact ECC correctly or overestimated by one ECC. The SDM met these conditions for 7/10 of the scenarios, the WMR model for 8/10 of the scenarios, and the NF-FF model for 9/10 of the scenarios. Additionally, The NF-FF model showed even more agreement with the measured ECC than the WMR model. This is further evidence that the NF-FF model is a more accurate reflection of actual conditions in a room. Contaminant particles can take some time to disperse throughout the room, depending on the ventilation and airflow rates, so there will typically be a higher concentration where the task is actually being performed (Nicas, 2017). On the other hand, the WMR model is less realistic since it assumes that contaminant particles are almost immediately mixed throughout the room. Additionally, these results are in line with findings from previous studies that have evaluated the efficacy of mathematical models in exposure estimates (Arnold Et al, 2017). It should also be noted that for some scenarios, the WMR gave a more accurate prediction than the NF-FF model did. Neither of these models are perfect representations of real world conditions. In a couple cases, a room's design, ventilation systems, or other factors may cause it to resemble a well-mixed room more closely. Take Scenario 9 for example. The fact that the WMR model gave a more accurate assessment than the NF-FF model did may be due to the dispersive nature of spray paints; these chemicals tend to spread around the room more quickly. Thus, the NF-FF model may have been inaccurate in assuming that the contaminant would have remained in the worker's immediate breathing zone after a certain period of time. Nonetheless, further research should be conducted on using mathematical models and other tools to evaluate exposure to spray paint in order to ascertain the most effective method to assess these scenarios. Additionally, more testing must be completed to provide further guidance on deciding if a scenario more closely corresponds to the WMR or NF-FF model.

Several unexpected outputs were observed in this study. For instance, the NF-FF model gave a higher estimate of contaminant concentration than the WMR model did, which is in line with earlier discussions. However, the opposite was true for scenario 10. This isn't a cause for concern. The WMR and NF-FF results for scenario 10 are within about 0.5% of each other, so this outlier isn't very significant and can be attributed to sampling variability. For the most part, the WMR model was fairly accurate. However, this was not the case for all the scenarios. The WMR model provided exposure estimates within one ECC for all of the scenarios except for scenario number four, where the model underestimated exposure by three ECCs. This result is concerning. The category four exposure in this scenario was estimated by the WMR model to be a category one exposure. This three category deviance would result in large differences in follow-up activity to ensure worker safety. However, this discrepancy may be explained, at least in part, by the peculiarities of the scenario. In this specific work environment, the worker was reaching into a large container that, when opened, releases highly concentrated methylene chloride into the air. The worker performed the task extremely close to the source of the contaminant. Given the nature of the situation, it's unlikely that the entire room was well-mixed. It clearly does not meet the assumptions of the WMR model, so the user wouldn't expect these results to reflect reality. Conversely, this situation fits well with the NF-FF model. This scenario highlights an important fact: There may be value in using multiple models together in evaluating a single workplace exposure. Using multiple low-cost tools can provide a multidimensional evaluation of a workplace that would more accurately reflect the range of exposures. Seeing the divergence between the outputs of the WMR and NF-FF models can lead to valuable insights about the scenario when it's not immediately apparent which model might fit best.

An important focus of this study was the evaluation of the SDM. The SDM, contrary to the IHMOD and other tools based in mathematical modeling, does not have large amounts of literature guiding appropriate usage by industrial hygienists. Thus, these results may be more significant in their impact on the field. The most noticeable result was that the SDM overestimated the exposure concentration for all seven of the scenarios for which it provided an output. A certain degree of inaccuracy was to be expected, given the small number of inputs and quickness of use. This tradeoff is acceptable since a reasonable level of accuracy was observed in the exposure assessments for which the SDM was used, as seen in Table III. Moreover, the tool was calibrated to slightly overestimate exposure levels in order to minimize the number of underestimates, which have more severe health consequences. However, the challenge is to strike a balance between simplicity and accuracy. The SDM underestimated exposure levels for Scenario 9, which was the only case study involving aerosols. Further testing of the Checklist on scenarios with aerosol contaminants may be necessary in order to guide usage of the tool in this area. Additionally, the level of control input may have been another source of error here. The subjective language used to define and select the engineering controls should be revised to reduce the uncertainty in outputs, as this input has a large impact on the predicted ECC. The SDM predicted a category two exposure for scenario 9 when the level of control was described as "General Ventilation." However, the SDM "Particulates, Fibers and Aerosols" setting does not have the option to select a lower level control. Thus, the tool may need to be updated to accommodate workplace settings with lower levels of control. Another area worthy of close attention was the SDM's evaluation of chemical mixtures, which is a relatively new capability that has not been extensively tested yet. The SDM overestimated both scenarios involving chemical mixtures by a significant margin: three ECCs. These results support additional research on the ability of a Checklist to accurately assess exposures to chemical mixtures. Because this study only evaluated two scenarios with chemical mixtures, any follow-up study must incorporate data points from a significantly larger number of mixtures. Conversely, these results might also be a signal that further guidance is needed for selecting the level of control, particularly with regard to mixtures. The SDM considered scenarios 7 and 8 category four exposures with the level of control being "poor." If the user had instead selected "Good-Displaced Air," which is the next highest level of control, the SDM would have only overestimated the exposure by one category instead of by three. Thus, clear instruction for selecting the appropriate level of control is instrumental for the SDM giving the most accurate exposure estimate.

Lastly, it is worth noting the dual goals of precision and accuracy. As seen in Figure VI, the IHMOD 2.0 tends to achieve a greater degree of precision as the standard deviation of its exposure estimates is considerably smaller than the standard deviation of the exposure estimates from the SDM 2.0. Thus, if an industrial hygienist desires a precise prediction of the exact concentration of the contaminant, the IHMOD 2.0 would likely be the better choice in that case. If, however, the industrial hygienist merely aims to provide an accurate exposure estimate in order to inform follow up actions to protect worker safety, the IHMOD 2.0 and the SDM 2.0 are not significantly different in this regard. As seen in Figure VI, the IHMOD 2.0 NF-FF model provided exposure estimates within one ECC of the measured result for 10/10 scenarios and the WMR model provided exposure estimates within one ECC of the measured result for 9/10 scenarios, which is not a significant departure from the 8/10 scenarios for which the SDM 2.0 was within one category. Evidently, the developers of the SDM sacrificed a small amount of accuracy for greater speed and efficiency of use. Therefore, this study shows that the SDM 2.0 would be a tremendous asset to industrial hygienists conducting exposure assessments in the workplace.

Conclusion

Despite the SDM's slight overestimation bias and both tools' varying degrees of precision, this study indicates that the SDM 2.0 and both models contained within the IHMOD 2.0 generally have good accuracy when evaluating exposure scenarios—predicted ECCs were off my more than one category for only three scenarios, meaning that for the vast majority of cases, there would have been no significant detriment to workers' safety. These results add to the current literature supporting estimation of exposures to a variety of common industrial solvents using the IHMOD 2.0, and more importantly, provide new evidence of the SDM 2.0's efficacy for non mixture solutions.

References

Arnold, S. F., Shao, Y., & Ramachandran, G. (2017, June 14). EVALUATING WELL MIXED ROOM AND NEAR FIELD FAR FIELD MODEL PERFORMANCE UNDER HIGHLY CONTROLLED CONDITIONS. Retrieved November 30, 2020, from https://pubmed.ncbi.nlm.nih.gov/28475481/

Arnold, Susan, Mark Stenzel, and Gurumurthy Ramachandran. (2006). Approaches to Improving Professional Judgment Accuracy. *A Strategy for Assessing and Managing Occupational Exposures, Third Edition* (pp. 88-107). 3rd ed., American Industrial Hygiene Association.

Arnold, Susan, Mark Stenzel, Daniel Drolet & Gurumurthy Ramachandran (2016) Using checklists and algorithms to improve qualitative exposure judgment accuracy, Journal of Occupational and Environmental Hygiene, 13:3, 159-168, DOI: 10.1080/15459624.2015.1053892

Gaffney, Shannon, Emily Moody , Meg McKinley , Jeffrey Knutsen , Amy Madl & Dennis

Paustenbach (2008) Worker Exposure to Methanol Vapors During Cleaning of Semiconductor Wafers in a Manufacturing Setting, Journal of Occupational and Environmental Hygiene, 5:5, 313-324, DOI: 10.1080/15459620801988014

Mulhausen, John, Joseph Damiano, and Elizabeth L. Pullen. (2006). Basic Characterization and Information Gathering. *A Strategy for Assessing and Managing Occupational Exposures, Third Edition* (pp. 19-32). 3rd ed., American Industrial Hygiene Association.

Mulhausen, John, and Joseph Damiano. Introduction. (2006). *A Strategy for Assessing and Managing Occupational Exposures, Third Edition* (pp. 1-12). 3rd ed., American Industrial Hygiene Association.

Nicas, Mark and John Neuhaus (2008) Predicting Benzene Vapor Concentrations with a Near Field/Far Field Model, Journal of Occupational and Environmental Hygiene, 5:9, 599-608, DOI: 10.1080/15459620802282375

Nicas, M. (2006). Estimating Airborne Exposure by Mathematical Modeling. *A Strategy for Assessing and Managing Occupational Exposures, Third Edition* (pp. 287-304). Fairfax, Virginia: American Industrial Hygiene Association.

Stenzel, Mark, and Susan Arnold. (2006). Rules and Guidelines to Facilitate Professional Judgments. *A Strategy for Assessing and Managing Occupational Exposures, Third Edition* (pp. 384-396). 3rd ed., American Industrial Hygiene Association.

Susan F. Arnold, Yuan Shao & Gurumurthy Ramachandran (2017) Evaluation of the well mixed room and near-field far-field models in occupational settings, Journal of Occupational and Environmental Hygiene, 14:9, 694-702, DOI: 10.1080/15459624.2017.1321843