HHS Public Access
Author manuscript
J Occup Environ Hyg. Author manuscript; available in PMC 2015 December 01.

Published in final edited form as:
J Occup Environ Hyg. 2013 ; 10(2): 97–108. doi:10.1080/15459624.2012.748627.

Exposure Models for the Prior Distribution in Bayesian Decision Analysis for Occupational Hygiene Decision Making

Eun Gyung Lee[1], **Seung Won Kim**[1,*], **Charles E. Feigley**[2], and **Martin Harper**[1]

[1]National Institute for Occupational Safety and Health, Exposure Assessment Branch, Health Effects Laboratory Division, Morgantown, West Virginia

[2]Department of Environmental Health Sciences, Arnold School of Public Health, University of South Carolina, Columbia, South Carolina

Abstract

This study introduces two semi-quantitative methods, Structured Subjective Assessment (SSA) and Control of Substances Hazardous to Health (COSHH) Essentials, in conjunction with two-dimensional Monte Carlo simulations for determining prior probabilities. Prior distribution using expert judgment was included for comparison. Practical applications of the proposed methods were demonstrated using personal exposure measurements of isoamyl acetate in an electronics manufacturing facility and of isopropanol in a printing shop. Applicability of these methods in real workplaces was discussed based on the advantages and disadvantages of each method. Although these methods could not be completely independent of expert judgments, this study demonstrated a methodological improvement in the estimation of the prior distribution for the Bayesian decision analysis tool. The proposed methods provide a logical basis for the decision process by considering determinants of worker exposure.

Keywords

AIHA exposure rating scheme; Bayesian decision analysis; COSHH Essentials scheme; prior decision distribution; structured subjective assessment (SSA); two-dimensional (2-D) Monte Carlo simulation

INTRODUCTION

The Bayesian decision analysis (BDA) method was developed by Hewett et al.[(1)] as a decision-making tool based on the exposure rating schemes of AIHA®. Using the conceptual framework of Bayesian statistics, the user's knowledge based on experience (i.e., expert judgment) can be incorporated into the decision-making process in a scientific and repeatable manner along with exposure monitoring data. The Bayesian method has three components of probability distributions: (1) a prior, $p(\theta)$, which uses either known information on parameters or subjective judgments by assigning joint probability distributions for all observable and unobservable parameters; (2) data Y, measured values of

Correspondence to: Eun Gyung Lee, NIOSH-HELD, 1095 Willowdale Road, Room 3030, Morgantown, WV 26505; dtq5@cdc.gov.
*Currently with: Public Health Department, Keimyung University, Daegu, South Korea

certain parameters (likelihood); and (3) the combination of these two sets of information to generate posterior probabilities $p(\theta|Y)$. The posterior probability is obtained through application of Bayes' theorem:

$$p(\theta|Y)=\frac{p(Y|\theta)p(\theta)}{\int p(Y|\theta)p(\theta)d\theta} \quad (1)$$

For each component, the BDA method determines the probability of the 95th percentile of the exposure distribution by classifying the exposure profile of a similar exposure group (SEG) into one of four exposure categories: highly-controlled (Category 1), well-controlled (Category 2), controlled (Category 3), or poorly controlled (Category 4). The SEG is defined as "Group of workers having the same general exposure pro-file for the agent(s) being studied because of the similarity and frequency of the tasks they perform, the materials and processes with which they work, and the similarity of the way they perform the tasks."[(2, p.342)] Table I shows an exposure category rating scheme where the exposure rating is assigned by comparing the 95th percentile of exposure distribution with the occupational exposure limit (OEL).[(3)] Note that Category 0 (Exposures are trivial to nonexistent) included in the 1991 AIHA rating scheme was eliminated in the 2009 AIHA rating scheme.[(3)] A final decision whether the SEG is over- or underexposed is based on the probability distribution of the posterior decision. For example, if the probabilities of posterior decision distribution are 0.7, 0.2, 0.1, and 0 for Categories 1, 2, 3, and 4, respectively, the user can conclude that the 95th percentile of exposure is most probably in Category 1 with 70% probability, or it has a 90% probability of being no higher than Category 2. It is easy for occupational hygienists and managers to understand results from this method and to make a final decision because the simulation result is represented as a distribution of decision probabilities. The BDA method has been disseminated to occupational professionals or risk managers via offering professional development courses at conferences. Currently, user friendly software for the BDA method is available, and it does not require profound knowledge of Bayesian statistics.

The BDA method can fully utilize small numbers of exposure measurements that would be too small for analysis by conventional statistics. Hewett et al.[(1)] pointed out that if the prior is accurate, less monitoring data would be sufficient to achieve high confidence in the estimated posterior. In real workplaces, however, it is often difficult to define an accurate prior distribution. The prior decision distribution can be represented in two ways. First, if a user has no prior knowledge regarding a process, a non-informative prior (i.e., assign the same weight for each category) can be used. In this case, the posterior decision distribution using the non-informative prior would be identical to the likelihood distribution indicating no contribution of the prior to yield the posterior distribution. Second, an informative prior decision distribution can be employed by allowing expert judgments. A significant correlation has been found between expert ratings and the average measurements of solvents and dust samples in five small factories.[(4)] However, several studies reported that the subjective assessments of exposure were often affected by various factors (e.g., experience, education, available information, and so on) that could be subject to cognitive biases.[(5–9)] Vadali et al.[(10)] discussed the drawbacks of using professional judgment to generate the probability of the prior decision distributions and suggested the two-zone near-field model using a two-dimensional (2-D) Monte Carlo (MC) scheme to replace professional judgments. It is expected that the proposed method should reduce uncertainty, although professional judgments were not completely eliminated.[10] However, the two-zone model does not consider contextual information of exposure determinants during job tasks. Also, some parameters such as the airflow rate between near- and far-field and the source emission rate are difficult to determine. A simple but more accurate method than professional judgment to specify BDA priors that can be widely accepted among professional and individuals not trained in occupational hygiene is needed.

The purpose of this study was to demonstrate two semi-quantitative methods that can be used for determining the probability of the prior decision distribution. These methods are (1) the Structured Subjective Assessment (SSA) method, and (2) the Control of Substances Hazardous to Health (COSHH) Essentials scheme. The SSA method was selected because it was the first version of a source-receptor approach and became a basic concept for developing advanced tools. The COSHH Essentials tool was chosen because of the ease of using this tool, especially for individuals not trained in occupational hygiene. Detailed information for each tool is described below. They have not previously been evaluated as a BDA tool. This article demonstrates how to employ these methods practically. In addition, the prior distribution using an expert judgment was included for comparison with other two methods. Two work-places, an electronic component manufacturing facility and a printing shop, were surveyed to demonstrate these methods.

OVERVIEW OF METHODS

Structured Subjective Assessment (SSA) Method

The SSA method is a semi-quantitative exposure model developed by Cherrie and Schneider[11] based on an earlier work by Cherrie et al.[12] This source-receptor approach uses descriptive information about job tasks to code factors related to exposure. It characterizes source emissions and the subsequent dispersion of contaminant in the work environment and accounts for workers' interaction with the dispersed contaminant. The first stage is to define job tasks, and each job task is classified as being performed in either the worker's near-field or far-field. The near-field source is defined as a volume of approximately 8 m^3 surrounding a worker's head, and the rest of the work room is defined as the worker's far-field. Then, for each source category, the intrinsic emission of the source (ε_i), which is an inherent property of a substance being handled and associated with the vaporization of liquids and the dustiness of solid materials, the handling or processing of the substance (h), and the presence of occupational hygiene controls ($1-\eta_{lv}$) are estimated. These factors are assumed to be independent and their product is defined as the active emission (ε_a). Table II shows general guidance to assign a value for each factor. Another emission not directly related to substance handling might occur during a task. This is defined as passive emission or fugitive sources (ε_p) and is typically much less than active emission.

The total emission (ε_T) is then estimated by summing the active emission (ε_a) and the passive emission (ε_p). Two additional terms, the time the sources are active (t_a) and the use of personal protective equipment ($1-\eta_{ppe}$), are added to estimate the exposure level during a task. Note that the inclusion of personal protection equipment does not allow comparison of the exposure levels to an OEL. In the present study, a default value of 1 was used unless the OEL is modified by the assigned protection factor.

With consideration of all these terms, the exposure during a task from the near-field (NF) source, C_{NF}, can be estimated as follows:[11]

$$C_{NF}=(\varepsilon_{i,NF}\cdot h_{NF}\cdot(1-\eta_{lv,NF})\cdot t_{a,NF}+\varepsilon_p)\cdot(1-\eta_{ppe}) \quad (2)$$

In a similar manner, the exposure during a task from the far-field (FF) source, C_{FF}, can be estimated as follows with the addition of another term, effectiveness of the dilution, d_{gv}.

$$C_{FF}=(\varepsilon_{i,FF}\cdot h_{FF}\cdot(1-\eta_{lv,FF})\cdot t_{a,FF}+\varepsilon_p)\cdot(1-\eta_{ppe})\cdot d_{gv} \quad (3)$$

Then, the total exposure of a worker is estimated by adding the contributions of the near-field and far-field exposures for all tasks (*n*):

$$C_T=\sum_{i=1}^{n}(C_{NF,i}+C_{FF,i})\cdot\Delta_i \quad (4)$$

where Δ_i is the fraction of time each task is performed. Note that assigned values in Table II are scores, and no units are involved. After the total exposure score of a worker for various tasks (C_T) is estimated, the exposure level can be calculated by multiplying C_T by the OEL of substance. A reasonably good correlation between the log-transformed measurements and estimates (average correlation coefficient 0.57 ranging from 0.31 to 0.93) was reported from a validation study for 63 job tasks involving five testing materials: man-made mineral fibers, asbestos, styrene, toluene, and mixed respirable dust.[11] This method was later incorporated into a control banding tool called Stoffenmanager, in The Netherlands,[13] and further refined in the development of the Advanced REACH Tool (ART) for inhalation exposure assessment.[14]

COSHH Essentials Scheme

Control banding approaches have been used to assess and manage occupational risk to help small and medium-sized enterprises where worker exposures were unlikely to be assessed. One of these banding tools is the Control of Substances Hazardous to Health (COSHH) Essentials model developed by the Health and Safety Executive (HSE) in Great Britain.[15–17] In this model, risk assessment is performed by combining a toxicological health hazard band using “risk phrases” (R-phrases) with an exposure potential band. While R-phrases can be found in safety data sheets, the information in these sources has been shown to be potentially suspect,[20] and the European Commission Joint Research Centre Institute for Health and Consumer Protection provides a standardized source of better quality. Based on the toxicity of substances, the health hazard band is divided into five categories, A (least hazardous), B, C, and D, and E (most hazardous). The exposure potential band is highly dependent on the amount of chemicals used during the task and volatility or dustiness of bulk chemicals. Table III shows predicted exposure potential band based on the exposure prediction level (EPL) and the existing control strategy for liquid. Then, a control method (i.e., risk management) is recommended based on the risk assessment. (For detailed information, refer to References 15–17.)

The COSHH Essentials model is a task-based model that has been validated by several researchers, and overall, good agreements between the model and observed exposure measurements were reported,[18–21] although a study by Jones and Nicas[22] was not in favor of the model. A web-based version of the COSHH Essentials model is currently available. One drawback of using the web version is that no existing controls are considered, whereas the printed version by Maidment[16] considers existing controls to estimate predicted exposure range (PER). For the present study, only exposure band using the estimated PER with existing controls was considered.

METHODS

Workplace Survey

Application 1: Electronic Component Manufacturing Facility—The workplace survey was carried out in a facility that manufactures solid tantalum and multilayer ceramic capacitors.[23] The current study was limited to the coating process of the tantalum capacitors with "silver ink," a suspension of silver in a polymeric binder using isoamyl acetate (IAA; 3-methylbut-1-yl ethanoate; CAS number 123-92-2) as a solvent, and the subsequent drying of the coated capacitors. A worker placed batches of tantalum "slugs" previously coated with manganese dioxide and graphite into a dipping tank containing "silver ink" and suspended from movable racks. This process took approximately 30 min per batch and was performed inside a laboratory hood (Task 1: Dipping). Then each batch was moved to a cart ("source" table) for visual inspection (Task 2: Inspection) and finally moved into a vented drying station (Task 3: Transfer to an oven). This study was performed over three full shifts on different days, and the production rates were 10, 24, and 14 batches per shift. During the survey, the eastern two-thirds of the room was not involved in any activities, and thus, all measurements were obtained from the silver dip area measuring 6.95 meters (L) × 9.14 meters (W) × 4.27 meters (H). Six measurements are the minimum recommended by AIHA strategy to estimate exposure levels of workers.[2] In this study, full-shift time-weighted average (TWA) personal exposures were measured from the two employees who were involved in the coating process on 3 consecutive days, yielding a total of six measurements. Diffusive samplers (Chemdisk; Assay Technologies, Pleasanton, Calif.) were used to collect IAA and were analyzed. The observed personal exposures were 8.2 and 8.5 mg/m^3 (Day 1), 5.0 and 20.9 mg/m^3 (Day 2), and 7.2 and 22.1 mg/m^3 (Day 3). The National Institute for Occupational Safety and Health (NIOSH) recommended exposure level (REL), the U.S. Occupational Safety and Health Administration (OSHA) permissible exposure limit (PEL), and the ACGIH® threshold limit value (TLV®)-TWA are given as 525 mg/m^3 (100 ppm). All measurements were considerably less than this value. The personal exposure measurements were used to generate the probabilities of the likelihood distribution.

Application 2: Printing Shop—The printing shop had three active printing presses, and only three employees were directly involved in running and cleaning the presses during the survey. Each employee was involved mainly in three tasks: (1) the cleaning of the rollers, (2) the printing process, and (3) the print preparation. The cleaning task was performed with a mixture of isopropanol (10–20% w/w, boiling point (BP) 83°C), acetone (40–50% w/w, BP 57°C), and VM&P naphtha (CAS No. 8032-32-4) at an operating temperature about 23°C. Each employee performed this task approximately 10 times per day, each time small quantities (< 2.5 l) being used for about 10 min. For the printing process, isopropanol (99% w/w) was used as a fountain solution additive stored in a container with a loose-fitting lid with a capacity of about 19 l. The room was controlled by general ventilation. Although no chemicals were used during the print preparation task, exposure measurements were obtained to evaluate possible accumulation in the room air due to the absence of a local exhaust ventilation system.

Thirty-one isopropanol TWA personal exposures were collected from three employees according to Method 1400 of the *NIOSH Manual of Analytical Methods (NMAM)*. Measurements ranged from 3 to 96 mg/m^3 (average TWA: 56 mg/m^3) were considerably less than OELs (NIOSH REL and OSHA PEL 980 mg/m^3(400 ppm); ACGIH TLV-TWA 490 mg/m^3 [200 ppm]). During the survey, no personal protective equipment except gloves was used. Detailed information is given elsewhere.[18]

The Prior Decision Distribution

SSA Method

Electronic component manufacturing facility: For the coating procedure, while a worker was doing one task, the other two tasks were treated as far-field sources. Worker exposure is a function of contaminant use, and for this batch, the process is expected to be proportional to the number of batches processed per shift during the coating procedure. Among the three tasks, the inspection of batches at a cart is considered the major source of the exposure because the worker had to bend over the cart to inspect the capacitors after the dipping process (i.e., direct exposure to IAA). The IAA personal exposure from the dipping task should be minimal because it was performed under a fume hood.

For a given scenario, MC simulation method can be used to generate random values representing exposure levels, C. For example, given the upper and lower bounds for parameters such as intrinsic emission (ε_i) and handling (h), a single value of ε_i and h is selected randomly and estimates the corresponding C. This procedure is repeated a sufficient number of times (e.g., 1000 or 10,000 times) to generate the exposure distribution. However, this distribution only provides a point estimate of the 95th percentile for the distribution, not its probability distribution. For the present study, a nest of two 1-D MC simulations (i.e., 2-D MC simulation), which is the same method that Vadali et al.[10] applied for the two-zone near-field model, was used to generate the probabilities of the prior decision distribution. The 2-D MC simulation uses two separate bounds for each upper and lower bound (U_1–U_2 and L_1–L_2) of parameters to consider the variability of the model parameters and the uncertainty from the lack of knowledge surrounding the model parameters. From the first round, the upper and lower boundaries of parameters were chosen randomly from the selected boundaries assuming uniform distribution in logarithmic scale. Uniform distribution was assumed due to a lack of parameter information, and a logarithmic scale was used because the scores were set up based on a logarithmic scale.[13] Then, 1000 random values of exposure levels within the boundaries chosen in the first round were selected from the second round of simulation. The 95th percentile exposure level among 1000 simulations was selected and its category was decided. The aforementioned step was repeated 1000 times.

The score of each parameter in Equations 2–4, to be used for the 2-D MC simulation, was assigned by an experienced occupational hygienist who was familiar with the coating procedure and who carried out the sample collection (Table IV). For the inspection and transfer of batches to an oven, two scores for the intrinsic emission (ε_i) were assigned to represent the upper (U) and lower (L) bounds. This was reasonable because the number of batches varied, typically ranging from 10–24 batches per shift. Then, the range of each bound (U_1–U_2 and L_1–L_2) was determined by selecting the upper and lower score of each parameter from Table II; for example, for the upper bound of $\varepsilon_i = 1$, the U_1 and U_2 were selected as 0.3 and 3, respectively. The selection method of U_1 and U_2 (or L_1 and L_2) might be considered to cause large errors due to a large difference between the scores. However, we selected the range of bounds in this manner to minimize subjective judgment as much as possible. Also, two scores for handling (*h*) all three tasks were selected to consider worst-case scenarios (possibly due to worker's behaviors that might considerably affect their exposure). For the present study, a default value of 1 was again used for the use of PPE unless the OEL is modified by the assigned protection factor. Given the assigned scores and ranges, the prior probability distribution was estimated using the 2-D MC simulation, programmed using an Excel Macro code (see the online supplementary file for the coding). The prior distribution can vary slightly at each simulation because of random sampling.

Printing shop: The same occupational hygienist who scored the capacitor coating process tasks assigned scores for each parameter (Table V). For the cleaning and printing tasks, two scores for the intrinsic emission (ε_i) and handling (*h*) were assigned to represent the upper and lower bounds. Then, the range of each bound (U_1–U_2 and L_1–L_2) was determined in the same manner as the coating process. After assigning all scores, the 2-D MC simulations were run 1000 times to generate the prior decision distribution.

COSHH Essentials Scheme

Electronic component manufacturing facility: Although the COSHH Essentials model was developed for a task-based model, Lee et al.[18] reported that the model worked well for both short-term (i.e., task-based) and full-shift evaluation in a small printing plant. In the present study, three tasks were combined using time fractions for each task. Table VI shows the physical characteristics and predicted exposure range (PER) of IAA for all tasks; the estimated PER is 2.6 (lower bound, L)–26.6 mg/m^3 (upper bound, U) for the dipping task and 26.6–266.0 mg/m^3 for the inspection and transfer to an oven. No historical data for these tasks were available for estimating the range of each bound. Thus, the boundaries of each bound (i.e., U_1–U_2 and L_1–L_2) were chosen from the recommended values by Hewett et al.,[1] 0.005 and 5 times of each bound. These boundaries were used to define the parameter space of a lognormal distribution in BDA. If a user has well-documented historical data for these specific tasks, the boundaries of each bound can be selected with more confidence. In the present study, each worker carried out all three tasks during a full shift. Therefore, it is reasonable to combine all three tasks using time fractions for a full shift (Table V).

Printing shop: For the three tasks, the estimated PER is 12.3 (L)–123.0 mg/m^3 (U) for both cleaning and print preparation tasks, and 123.0–1230.0 mg/m^3 for the printing task. The detailed method to estimate PER is given elsewhere.[21] The same factors, 0.005 and 5 times, were used for the boundaries of each bound.

For both workplace applications, the 2-D MC simulations were run 1000 times to obtain the probability of the prior decision distribution.

Expert Judgment—A subject assessment was performed by an occupational hygienist who was familiar with the tasks. For the electronic component manufacturing facility, the expert assigned the prior probability distribution as 0.6, 0.4, 0.0, and 0.0 for AIHA Categories 1, 2, 3, and 4, respectively based on the description of work tasks. For the printing shop, the same expert assigned the prior probability distribution as 0.2, 0.6, 0.2, and 0.0 for AIHA Categories 1, 2, 3, and 4, respectively.

The Likelihood and Posterior Decision Distribution

The probability of likelihood decision distribution was generated based on six personal exposure measurements for the electronic component manufacturing facility and 31 personal exposure measurements for the printing shop assuming a log-normal distribution using Hewett's software (version 1.27, IH-DataAnalyst, Exposure Assessment Solutions, Inc., Morgan-town, W.Va.). The posterior decision distribution, which drives the final decision-making, was determined by the product of the prior and the likelihood decision function.

RESULTS

SSA Method

For the electronic component manufacturing facility, the probabilities of the prior decision distribution were almost equal for Categories 1 and 2 and zero probability for Categories 3 and 4 (Figure 1). As expected from exposure measurements (average IAA = 12 mg/m^3, only 2.3% of the OEL 525 mg/m^3), the likelihood function based on the exposure measurements yielded the highest decision probability in Category 1 (0.804). The probabilities of the posterior were very similar to those of the likelihood distribution, indicating that the prior did not influence the posterior. The posterior decision probability yielded a Category 1 decision where IAA exposures would infrequently exceed 10% of the OEL (highly controlled). Alternatively, a user can conclude that workers' exposure to IAA would not exceed 50% of the OEL, leading to a decision that no further controls were necessary. Overall, the prior did not affect the likelihood in a way that could modify the posterior distribution.

For the printing shop, the SSA method generated the highest probability in Category 2 and the second highest probability in Category 3 (Figure 2). The likelihood probabilities were 0.000, 0.679, 0.315, and 0.006 for Categories 1, 2, 3, and 4, respectively. As a final decision, the posterior yielded a Category 2 decision where isopropanol exposures would infrequently exceed 50% of the limit and rarely exceed the limit. The high probability of Category 2 in the prior decision distribution added more weight to the likelihood distribution and thus resulted in a high probability (0.941) for Category 2 in the posterior. This application showed that the prior impacted the likelihood yielding higher probability of Category 2 in the posterior.

COSHH Essentials Scheme

For the electronic component manufacturing facility, the probability of the posterior decision distribution yielded the same final decision, Category 1 (highly controlled), as the SSA method shown in Figure 1. This scheme also shows satisfactory results (i.e., no requirement of advanced controls) because the probability profile of exposure was no more than a Category 2 (100%) indicating well-controlled condition. Like the SSA method, almost no influence of the prior on the posterior was observed.

For the printing shop, unlike the SSA method, the prior decision distribution generated a profile showing little differences among categories (Figure 2). When the prior was combined with the likelihood, the posterior yielded a Category 2 (well-controlled) decision with a probability of 0.8. Alternatively, since 0.191 probability was observed in Category 3 of the posterior, a user can conclude that workers' exposure to isopropanol from the printing work would infrequently exceed the OEL ($X_{0.95} \leq$ OEL). The combined probability of Categories 1 and 2 in the prior distribution affected the likelihood and resulted in 0.801 probability of Category 2 in the posterior distribution. Also, the probability of Category 4 in the likelihood was increased from 0.006 to 0.009 in the posterior decision distribution although the magnitude of the change is minimal.

Expert Judgment

For the electronic component manufacturing facility (Figure 1), an impact of the prior was not observed in the posterior because the probability decision of the expert contributed only to Categories 1 and 2 in the prior showing the same pattern of the likelihood.

For the printing shop (Figure 2), the probability of Category 2 (0.6) in the prior attributed about 20% more weight to the Category 2 of the likelihood, increasing that category's posterior probability from 0.68 to 0.87.

DISCUSSION

SSA Method

The SSA method has several advantages. First, it does not require any measurements to generate the prior decision distribution, while the two-zone method requires measurements for parameters such as contaminant emission rate, dilution airflow rate, and the rate of air exchange between the two zones. Second, the SSA considers several parameters that are not counted in the COSHH Essentials scheme or the two-zone method.[10] For example, handling of substances (h), PPE control ($1\text{-}\eta_{pp}$), and passive emission (ε_p) are not included in the other methods. Note that a default value of 1 should be used for $1\text{-}\eta_{pp}$ unless the OEL is modified by the assigned protection factor. These are exposure determinants that impact the exposure level of the workers. Third, the user can avoid a reliance of subjective judgments as much as possible by following general guidance to assign values for each parameter. It is necessary to define ranges of lower (L) and upper (U) bound, i.e., L_1–L_2 and U_1–U_2 to implement the 2-D MC simulation. In the COSHH Essentials, 0.005 and 5 times of estimated values were assumed to define ranges due to a lack of historical data for this specific process. An incorrect assumption of the boundaries could dramatically change the results of the posterior decision probabilities. In the SSA method, the ranges were determined by selecting the upper and lower score of each bound to minimize any effect of subjective judgments.

The estimation of the prior decision distribution can be improved by providing more structured and precise categories of parameters to be used in the method.[24,25] Both SSA and Stoffenmanager methods use generic classes with descriptive explanation to obtain scores. One notable factor that was not considered is energy transfer variables (e.g., the type and amount of energy transfer during an activity).[25] "Energy transfer" accounts for the release of a substance *"from the parent material or from a contaminated surface because of energy transfer. Various types of energy transfer are relevant: i.e. motive forces, gravitational and impaction forces, friction, pressure drop, heat*." [26, p.991]

More recently, the ART mechanistic model integrating several energy transfer terms were developed based on the same approach to model worker's inhalation exposure.[14] Compared with the Stoffenmanager and SSA methods, ART provides a more structured characterization of intrinsic emission, local control, and dispersion based on room sizes. For example, only one score for "local exhaust ventilation" control exists in the SSA and Stoffenmanager, but in the ART model, different scores are assigned according to the hood types, such as canopy hoods, fume cupboard hoods, horizontal/downward laminar flow booth, and fixed/movable capturing hoods. The ART mechanistic model explained about 10% more variance compared with the Stoffenmanager tool.[27] For the present study, the categorization by the ART model was not considered for simplicity in terms of utilizing qualitative assessment approaches. If a user is familiar with the ART model, the ART mechanistic model can be applied to reduce uncertainty. The SSA method cannot be completely independent of subjective judgment because the scores for each parameter are assigned by an occupational hygienist or non-occupational hygienist who is familiar with the tasks. Nevertheless, the SSA method provides a more transparent procedure to determine the prior decision distribution compared with using the prior based only on expert judgment.

COSHH Essentials Scheme

The COSHH Essentials scheme does not require any parameter measurements to determine the probability of the prior distribution. It considers only the volatility and amount of chemical used during the task that can be easily obtained. Another advantage is that it requires less professional knowledge compared with the SSA method. An existing control such as local exhaust or containment control can be considered in PER estimation using the printed version,[16] whereas only general ventilation is assumed for the web version. Thus, for this purpose, the printed version is recommended.

An influence of the prior distribution on the final decision was observed for the printing process, while no impact was observed for the coating procedure. The prior distribution using the COSHH Essentials scheme was considerably different from the prior using the SSA method for the printing process. There are several possible reasons for this difference. First, exposure level estimates are based on fewer determinant factors in COSHH Essentials than in the SSA method. For example, room sizes are not considered in the COSHH Essentials. Second, the ranges of PER were wide: 12.3–123.0 mg/m^3 for the cleaning and print preparation tasks and 123.0–1230.0 mg/m^3 for the printing task. While a wide range of PER provides a substantial margin of safety to compensate for the use of fewer determinants, this tenfold range of exposure cannot be modified and could possibly generate higher exposure rating in Category 4 than the SSA method. A third reason could be the assumption of boundaries (0.005 and 5 times of each upper and lower bound) due to a lack of historical exposure measurements. This assumption increases the risk of producing an unreasonable prior probability distribution. If a user has little experience with the process and no historical data are available, it would be sensible to compare the COSHH results with the outputs of the other two methods, the SSA and the expert judgments. The COSHH Essentials scheme also cannot be made completely free from subjective judgments. However, this tool can also act as a bridge between pure expert judgments and exposure measurements.

Expert Judgment

For the workplaces tested in this study, the posterior distributions using the expert judgment-based prior distributions were similar to those using the SSA and the COSHH Essentials for both IAA and isopropanol. Based on this observation, a user can be very confident about his/her judgment for estimating the prior distribution. Although it is not the case of this study, under some circumstances the subjective assessment can cause biases.[(5–9)] If the findings using expert judgment were significantly different compared with those two semi-quantitative methods, for example, the user could collect more samples to have greater confidence in the decision.

CONCLUSION

This study demonstrated a methodological improvement in the estimation of prior distribution for the BDA tool. For example, the influence of the prior in the printing process showed the benefit of the Bayesian approach because the decision was based not only on a logical approach using the SSA method but also on exposure measurements.

Estimation of the true uncertainty for each method (i.e., the SSA method, COSHH Essentials method, and expert judgment) would be impossible in practice, although the 2-D MC simulations for the SSA and the COSHH Essentials method consider uncertainty. Nevertheless, the uncertainty from the prior distribution can be minimized by providing more accurate information (e.g., the type and amount of energy transfer during an activity) regarding model input parameters or exposure determinants. For example, we selected a general guideline to assign scores for each parameter for the SSA method. Users with an occupational hygiene background can use a more complex guideline (e.g., ART mechanistic model) to reduce uncertainty.

Users should be cautious about selecting a method to determine prior decision distributions. A user can select a method for generating prior decision distribution based on the available information for specific tasks. For example, in a situation where a user has only a few exposure measurements and is not sure whether these measurements are representative for a specific task, it would be better to use both SSA and COSHH Essentials methods and compare the outputs. If these methods yield the same or similar prior decision distribution, the favorable concordance of these methods can be an important comfort factor in decision making. If the results of the methods are different or if large discrepancies between the prior and the likelihood are observed, collection of additional exposure data might be necessary. In the case where prior distribution determined from purely subjective judgments is considerably different from the distributions provided by these methods, these methods can be used to calibrate an expert's judgment.

The benefits of using the proposed methods are: (1) the likelihood distribution with a low precision (i.e., very few data points) is improved by combining the prior distribution to generate the posterior distribution; (2) the SSA and COSHH Essentials methods provide more transparency in decision making than a subjective judgment; and (3) the proposed methods can be used to calibrate subjective judgments. A limitation of the semi-quantitative methods is that the methods cannot be completely independent of expert judgments. However, these approaches could be more reliable than purely subjective judgments by an occupational professional because decisions are explicitly derived from knowledge of the factors that determine worker exposure. In addition, logical application of these methods would generate a detailed justification and documentation of the decision process.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

The authors are sincerely thankful to Dr. Gurumurthy Ramachandran (University of Minnesota) and Dr. Abbas Virji (NIOSH/Division of Respiratory Disease Studies) for reviewing this manuscript prior to journal submission. The authors also would like to thank Nicholas Dow Schnaufer and J. Mark Brooks who helped with the field survey and sample collection. This project was funded internally by the National Institute for Occupational Safety and Health (Project HELD 0004-External validation of Tier 1 and Tier 2 models under REACH).

The findings and conclusions in this report are those of the author(s) and do not necessarily represent the official position of the Centers for Disease Control and Prevention. ACGIH TLVs are provided for information purposes only and should not be construed as implying endorsement.

References

1. Hewett P, Logan P, Mulhausen J, et al. Rating exposure control using Bayesian decision analysis. J Occup Environ Hyg. 2006; 3:568–581. [PubMed: 16998991]
2. Ignacio, Joselito S.; Bullock, William H., editors. AIHA. A Strategy for Assessing and Managing Occupational Exposures. 3. Fairfax, Va: AIHA; 2006.

3. Keil, CB.; Simmons, CE.; Anthony, TR., editors. AIHA. Mathematical Models for Estimating Occupational Exposure to Chemicals. 2. Fairfax, Va: AIHA; 2009.
4. Kromhout H, Oostendorp Y, Heederik D, Boleij JSM. Agreement between semiquantitative exposure estimates and quantitative exposure measurements. Am J Ind Med. 1987; 12:551–562. [PubMed: 3687951]
5. Hawkins NC, Evans JS. Subjective estimation of toluene exposures: A calibration study of industrial hygienists. Appl Ind Hyg. 1998; 4:61–68.
6. Walker KD, Catalano P, Evans JS, Hammitt JK. Use of expert judgment in exposure assessment, Part II: Calibration of expert judgments about personal exposures to benzene. J Expo Anal Environ Epidemiol. 2003; 13:1–16. [PubMed: 12595879]
7. Macaluso M, Delzell E, Rose V, Perkins J, Oestenstad K. Inter-rater agreement in the assessment of solvent exposure at a car assembly plant. Am Ind Hyg Assoc J. 1993; 54:351–359. [PubMed: 8362756]
8. De, Cock J.; Kromhout, H.; Heederik, D.; Burema, J. Experts' subjective assessment of pesticide exposure in fruit growing. Scand J Work Environ Health. 1996; 22:425–432. [PubMed: 9000309]
9. Ramachandran G. Retrospective exposure assessment using Bayesian methods. Ann Occup Hyg. 2001; 45:651–667. [PubMed: 11718661]
10. Vadali M, Ramachandran G, Mulhausen J. Exposure modeling in occupational hygiene decision making. J Occup Environ Hyg. 2009; 6:353–362. [PubMed: 19326267]
11. Cherrie JW, Schneider T. Validation of a new method for structured subjective assessment of past concentrations. Ann Occup Hyg. 1999; 43:235–245.
12. Cherrie JW, Schneider T, Spankie S, Quinn M. A new method for structured, subjective assessments of past concentrations. Ann Occup Hyg. 1996; 3:75–83.
13. Marquart H, Heussen H, Feber M, et al. 'Stoffenmanager', a web-based control banding tool using an exposure process model. Ann Occup Hyg. 2008; 52:429–441. [PubMed: 18587140]
14. Fransman W, Tongeren MV, Cherrie JW, et al. Advanced REACH Tool (ART): Development of the mechanistic model. Ann Occup Hyg. 2011; 55:957–979. [PubMed: 22003239]
15. Brooke I. A UK scheme to help small firms control health risks from chemicals: Toxicological considerations. Ann Occup Hyg. 1998; 42:377–390. [PubMed: 9738435]
16. Maidment S. Occupational hygiene considerations in the development of a structured approach to select chemical control strategies. Ann Occup Hyg. 1998; 42:391–400. [PubMed: 9738436]
17. Russell R, Maidment S, Brooke I, Topping M. An introduction to a UK scheme to help small firms control health risks from chemicals. Ann Occup Hyg. 1998; 42:367–376. [PubMed: 9738434]
18. Lee E, Harper M, Bowen RB, Slaven JE. Evaluation of COSHH Essentials: methylene chloride, isopropanol, and acetone exposures in a small printing plant. Ann Occup Hyg. 2009; 53:463–474. [PubMed: 19435980]
19. Tischer M, Bredendiek-Kämper R, Poppek U. Evaluation of the HSE COSHH Essentials exposure predictive model on the basis of BAuA field studies and existing substances exposure data. Ann Occup Hyg. 2003; 47:557–569. [PubMed: 14530182]
20. Hashimoto H, Toshiaki G, Nobutoyo N, et al. Evaluation of the control banding method—Comparison with measurement-based comprehensive risk assessment. J Occup Health. 2007; 49:482–492. [PubMed: 18075208]
21. Lee E, Slaven JE, Bowen RB, Harper M. Evaluation of COSHH Essentials model with a mixture of organic chemicals at a medium plant. Ann Occup Hyg. 2011; 55:16–29. [PubMed: 21047985]
22. Jones RM, Nicas M. Evaluation of COSHH Essentials for vapour degreasing and bag filling. Ann Occup Hyg. 2006; 50:137–147. [PubMed: 16172141]
23. Feigley CE, Do T, Khan J, et al. Deriving realistic source boundary conditions for a CFD simulation of concentrations in workroom air. Ann Occup Hyg. 2011; 55:410–420. [PubMed: 21422277]
24. Semple SE, Proud LA, Tannahill SN, et al. A training exercise in subjectively estimating inhalation exposures. Scand J Work Environ Health. 2001; 27:395–401. [PubMed: 11800327]
25. Tielemans E, Schneider T, Goede H, et al. Conceptual model for assessment of inhalation exposure: Defining modifying factors. Ann Occup Hyg. 2008; 52:577–586. [PubMed: 18787181]

26. Marquart H, Schneider T, Goede H, et al. Classification of occupational activities for assessment of inhalation exposure. Ann Occup Hyg. 2011; 55:989–1005. [PubMed: 21926067]

27. Schinkel J, Warren N, Fransman W, et al. Advance REACH tool (ART): Calibration of the mechanistic model. J Environ Monit. 2011; 13:1374–1382. [PubMed: 21403945]

Author Manuscript
Author Manuscript
Author Manuscript

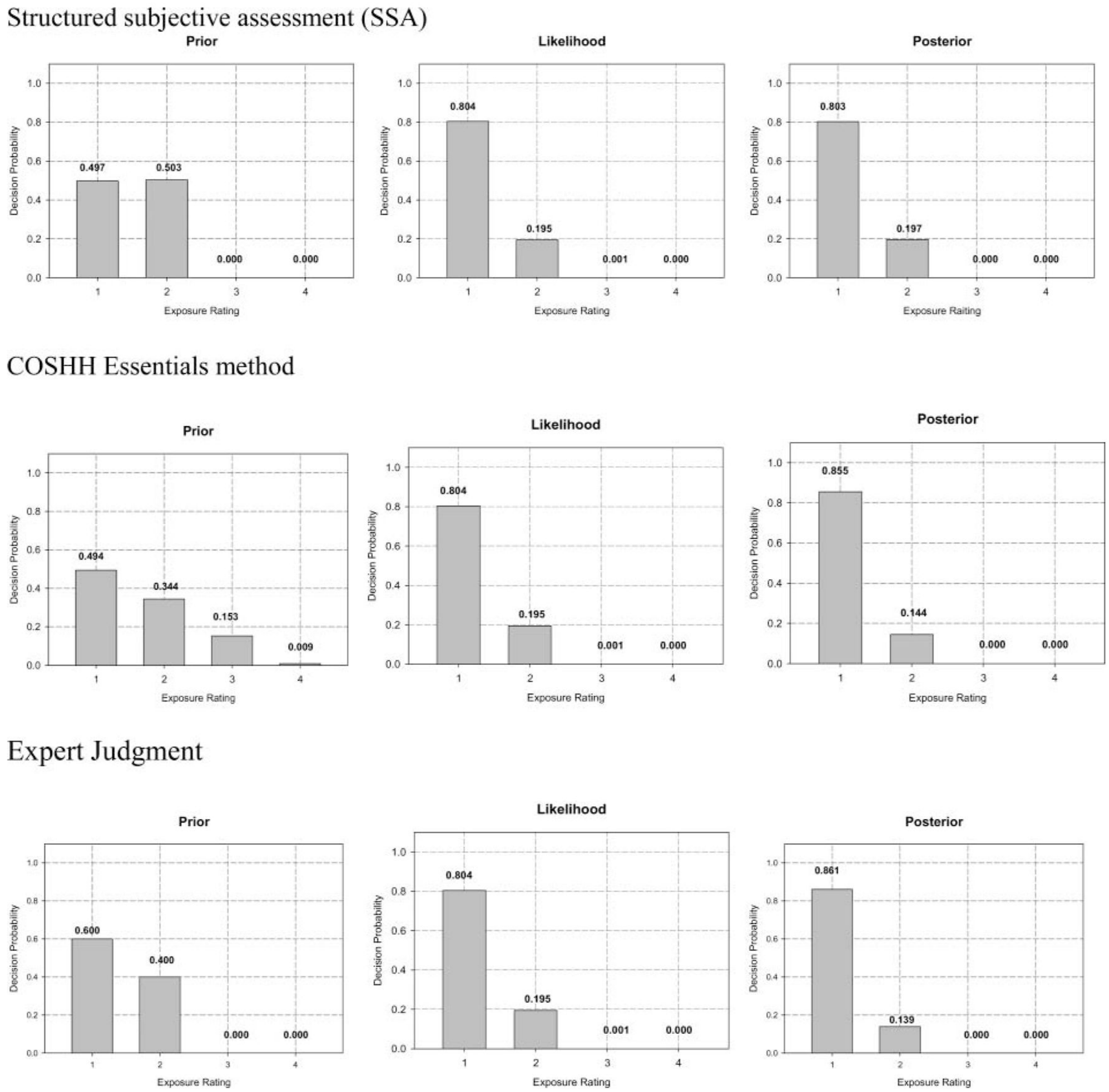

FIGURE 1.

Posterior decision distribution using different methods for determining the decision probability of the prior (Isoamyl acetate; OEL-525 mg/m^3 [ACGIH® TLV®, NIOSH REL, and OSHA PEL]; three tasks [dipping, inspection, and transfer to an oven] were combined using time fractions).

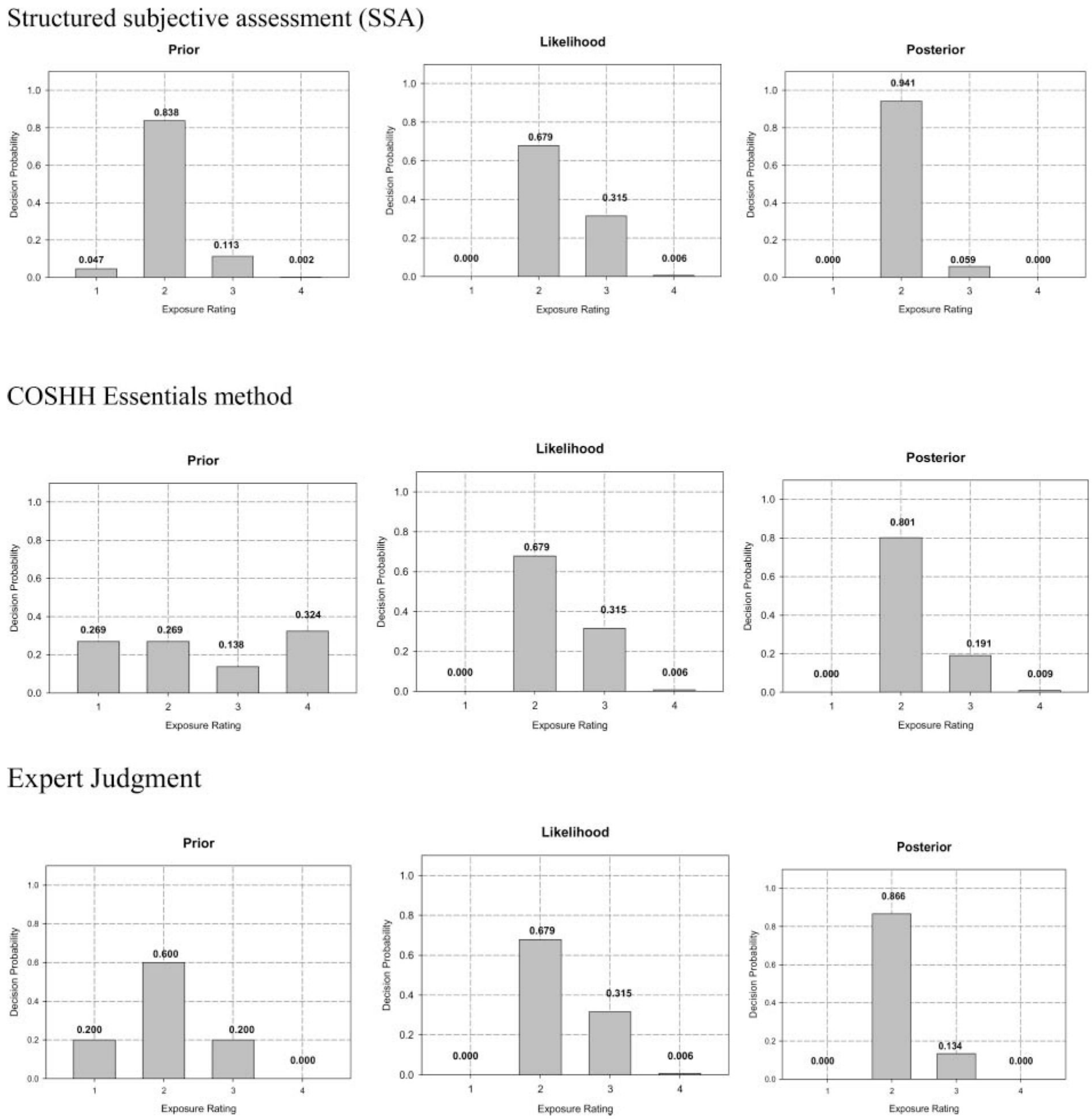

FIGURE 2.

Posterior decision distribution using different methods for determining the decision probability of the prior (Isopropanol; OEL-200 ppm [ACGIH TLV] and 400 ppm [NIOSH REL and OSHA PEL]); three tasks [cleaning, printing process, and print preparation] were combined using time fractions).

TABLE I

AIHA Exposure Category Rating Scheme

AIHA Exposure Rating	Proposed Control Zone Description	Qualitative Description	AIHA Recommended Statistical Interpretation
1	Highly controlled (HC)	Exposures infrequently exceed 10% of the limit[B]	$X_{0.95}$[A] $\leq$ 0.10 OEL
2	Well controlled (WC)	Exposures infrequently exceed 50% of the limit and rarely exceed the limit[B,C,D]	0.10 OEL $<$ $X_{0.95}$ $\leq$ 0.50 OEL
3	Controlled (C)	Exposures infrequently exceed the limit[B,D]	0.5 OEL $<$ $X_{0.95}$ $\leq$ OEL
4	Poorly controlled (PC)	Exposures frequently exceed the limit[D]	OEL $<$ $X_{0.95}$

[A] $X_{0.95}$ = 95th percentile of exposure distribution.

[B] “Infrequently” refers to an event that occurs no more than 5% of the time.

[C] “Rarely” refers to an event that occurs no more than 1% of the time.

[D] High concentrations are defined as concentrations that exceed the TWA limit or STEL.

Source: Reference 2.

TABLE II

General Guidance to Assign a Score for SSA Method

	Description	Meaning
Intrinsic emission (ε_i)		
10	Very high	Very dusty, or vapor produced from high pressure or temperature in handling
3	High	Large amount of dust or vapor produced in handling
1	Moderate	Some dust or vapor produced in handling
0.3	Low	Little dust or vapor produced in handling
0.1	Very low	Very little dust or vapor produced
0	None	Contaminant cannot be released
Handling (h)		
10	Very high	High energy impact, crushing, and evaporation from an aerosol
3	High	Breaking dropping 0.5 to 2 m, bubbling through liquid
1	Moderate	Dropping less than 0.5 m, pouring with splashing
0.3	Low	Lifting, stacking, pouring
0.1	Very low	Careful lifting
0	None	No handling or processing
Local control ($1-\eta_{lv}$)		
1	None	No local controls
0.3	Some controls	Local ventilation installed or other controls in use
0.1	Effective controls	Well designed and maintained local ventilation or other efficient controls
Passive emission (ε_p)		
0.3		Very poor house keeping
0.1		Some sources of emission such as leaking
0		No possibility of passive emission
PPE control ($1-\eta_{pp}$)		
1		No PPE
0.3		Limited controls
0.1		Effective controls
Duration of exposure (t_a)[A]		
1		4–8 hr a day
0.50		2–4 hr a day
0.25		0.5–2 hr a day
0.06		1–30 min a day
Effectiveness of the dilution (d_{gv})		
1		Poorly ventilated small rooms
0.3		Larger rooms or rooms with good general ventilation
0.1		Large well ventilated rooms

[A]Scores for each factor were from Cherrie and Schneider[11] except for the duration of exposure (t_a) where scores were from Marquart et al.[13]

TABLE III

Predicted Exposure Range in Air Concentration (ppm)

	Exposure Prediction Level (EPL)			
Existing engineering control during task	**EPL4**	**EPL3**	**EPL2**	**EPL1**
General ventilation (no engineering controls)	> 500	50–500	5–50	< 5
Local exhaust ventilation or other engineering containment controls (no requirement for a closed system)	50–500	5–50	0.5–5	< 0.5
Containment controls	0.5–5	0.5–5	0.05–0.5	< 0.05

Note: EPL1- ml quantities of low volatility material; EPL2- ml quantities of medium/high volatility material and m^3/liter quantities of low volatility material; EPL3-m^3 quantities of medium volatility material and liter quantities of medium/high volatility material; EPL4- m^3 quantities of high volatility material; PER as a TWA airborne concentration in the personal breathing zone is a function of the exposure potential level and presence of engineering controls. Source: Maidment.[16]

TABLE IV

Assigned Scores for the Coating Procedure (SSA Model)

	Dipping			Inspection			Transfer to an Oven		
Task	**NF**[A]	**FF**$_{ins}$[B]	**FF**$_{tra}$[C]	**NF**	**FF**$_{dip}$[D]	**FF**$_{tra}$	**NF**	**FF**$_{dip}$	**FF**$_{ins}$
Intrinsic emission (ε_i)	0.1	0	0	0.3, 1[E]	0	0	0.1,0.3[E]	0	0
Handling (h)	0.1, 0.3[F]	0	0	0.1,0.3[F]	0	0	0.1, 0.3[F]	0	0
Local control ($1\text{-}\eta_{lv}$)	0.1	1	1	1	0.1	1	1	0.1	1
Duration of exposure (t_a)	1	1	1	0.5	0.5	0.5	0.25	0.25	0.25
Passive emission (ε_p)	0	0.1	0.1	0	0	0.1	0	0	0.1
PPE control ($1\text{-}\eta_{pp}$)[G]	1	1	1	1	1	1	1	1	1
Effectiveness of the dilution (d_{gv})	n/a	0.3	0.3	n/a	0[H]	0.3	n/a	0[H]	0.3
Time fraction (Δ_i)		0.55			0.40			0.05	

[A]NF = near-field source from a worker.

[B]FF_{ins} = far-field source of inspection work.

[C]FF_{tra} = far-field source of transferring a coated batch to an oven.

[D]FF_{dip} = far-field source of dipping work.

[E]Two scores were selected for the inspection and transfer to an oven because the number of batches produced per shift varied.

[F]The higher score (0.3 for all three tasks) was selected to consider worst scenarios.

[G]A default value of 1 was used.

[H]Selected 0 because the dipping work was done only under a fume hood (i.e., local ventilation).

TABLE V

Assigned Scores for the Printing Process (SSA Model)

Task	Cleaning			Printing Process			Print preparation		
	NF[A]	FF_{print}[B]	FF_{pp}[C]	NF	FF_{cle}[D]	FF_{pp}	NF	FF_{cle}	FF_{print}
Intrinsic emission (ε_i)	0.3, 1[E]	0	0	1, 3[E]	0	0	0	0	0
Handling (h)	0.1, 0.3[F]	0	0	0.3, 1[F]	0	0	0	0	0
Local control ($1-\eta_{lv}$)	1	1	1	1	1	1	1	1	1
Duration of exposure (t_a)	0.25	0.25	0.25	0.5	0.5	0.5	1	1	1
Passive emission (ε_p)	0	0.1	0.1	0	0.1	0.1	0	0.1	0.1
PPE control ($1-\eta_{pp}$)[G]	1	1	1	1	1	1	1	1	1
Effectiveness of the dilution (d_{gv})	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Time fraction (Δ_i)		0.1			0.40			0.5	

[A] NF = near-field source from a worker.

[B] FF_{print} = far-field source of printing work.

[C] FF_{pp} = far-field source of print preparation work.

[D] FF_{cle} = far-field source of cleaning work.

[E] Two scores were selected for the cleaning and printing process tasks to consider varying amount of printing work.

[F] The higher score (0.3 for the cleaning task and 1 for the printing process task) was selected to consider worst scenarios.

[G] A default value of 1 was used.

TABLE VI

Physical Characteristics and Predicted Exposure Range for IAA

Task	Dipping	Inspection	Transfer to an Oven
Volatility	Medium	Medium	medium
Boiling point (°C)	142	142	142
Quantity[A]	Small	Small	Small
Control method	Local exhaust ventilation	General ventilation	General ventilation
PER (mg/m^3)	2.6–26.6	26.6–266.0	26.6–266.0
Range of upper and	U = 0.53–79.9	U = 5.3–799.0	U = 5.3–799.0
lower bounds (mg/m^3)	L = 0.05–8.0	L = 0.5–79.9	L = 0.5–79.9
Time fraction	0.55	0.40	0.05

[A]Quantity: small < 2.5 l; medium 2.5 – 1000 l; large > 1 m^3.