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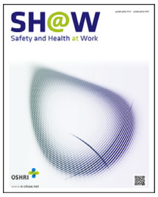

Original article

Comparative Study of Exposure Assessment of Dust in Building Materials Enterprises Using ART and Monte Carlo

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ABSTRACT

Background: Dust generated during the processing of building materials enterprises can pose a serious health risk. The study aimed to compare and analyze the results of ART and the Monte Carlo model for the dust exposure assessment in building materials enterprises, to derive the application scope of the two models.
Methods: First, ART and the Monte Carlo model were used to assess the exposure to dust in each of the 15 building materials enterprises. Then, a comparative analysis of the exposure assessment results was conducted. Finally, the model factors were analyzed using correlation analysis and the scope of application of the models was determined.
Results: The results show that ART is mainly influenced by four factors, namely, localized controls, segregation, dispersion, surface contamination, and fugitive emissions, and applies to scenarios where the workplace information of the building materials enterprises is specific and the average dust concentration is greater than or equal to 1.5 mg/m^3. The Monte Carlo model is mainly influenced by the dust concentration in the workplace of building materials enterprises and is suitable for scenarios where the dust concentration in the workplace of the building materials enterprises is relatively uniform and the average dust concentration is less than or equal to 6mg/m^3.
Conclusion: ART is most accurate when workplace information is specific and average dust concentration is $>$ 1.5 mg/m^3; whereas, The Monte Carlo model is the best when dust concentration is homogeneous and average dust concentration is $<$ 6 mg/m^3.

1. Introduction

The dust generated during the processing of building materials enterprises can pose a serious health risk [1]. The current research on dust in building materials enterprises mainly focuses on the study of dust removal technology [2] and the comprehensive evaluation of dust [3]. Some scholars have also studied dust exposure in building material enterprises, but the exposure assessment process is complicated and computationally intensive due to the lack of selection of an appropriate exposure assessment model [4]. As a key part of dust risk assessment, exposure assessment can qualitatively or quantitatively evaluate the dust ingested into the human body through the respiratory, skin, and digestive tracts [5] and obtain dust exposure concentrations and exposure doses to clarify and judge the possibility and severity of health hazards to workers so that corresponding preventive measures can be taken to effectively reduce the health hazards caused by dust in building materials enterprises [6,7].

Suitable models need to be selected when conducting dust exposure assessments [8]. There are many international dust exposure assessment models, such as Estimation and Assessment of Substance Exposure (EASE) [9], EMKG-EXPO-TOOL, European Ecotoxicology and Toxicology Center (ECETOC TRA) [10], Stoffenmanager (SM) [11], and Advanced REACH Tool (ART) [12]. Compared with other models, ART provides more specific parameter options, is easier to operate, and can be combined with the

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built-in Bayesian database to correct the exposure assessment results, which greatly reduces the subjectivity of the assessment process and makes the results more reliable [13]. The parameters required by ART in exposure assessment are easily affected by the working environment, and the professional knowledge of the personnel in exposure assessment will also have a certain influence on the selection of parameters. The Monte Carlo model can avoid such influence in exposure assessment, but different formulas need to be substituted for different workplaces, and lack of relevant databases for reference. They represent two different exposure assessment models, each with its own advantages and disadvantages in dust exposure assessment.

ART and the Monte Carlo model were used for dust exposure assessment. Research on the use of ART for dust exposure assessment has been related to paint-spraying enterprises and respirable dust from pharmaceutical plants [14], and some scholars have improved ART and extended its use to include fumes from welding and low-volatile liquids [15,16]. Simulation of the Monte Carlo model can be achieved by using Crystal Ball [17]. Regarding exposure assessment, the Monte Carlo method has also been found in increasingly common applications in food processing, road transport, statistics, public health, and other fields [18–20], but its applicability has not been proven.

This article compares the differences between using ART and Monte Carlo models to evaluate the dust exposure of building materials enterprises, and obtains the applicability of the two models, providing reference for the selection of dust exposure assessment models for building materials enterprises.

2. Materials and methods

2.1. ART and Monte Carlo model

ART is the most sophisticated tool used to assess exposure levels under the EU Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) regulation [21]. The Monte Carlo model is a statistical method of repeatedly calculating a quantity using computer-generated factors that can reduce the influence of assessment uncertainty and subjective factors [22]. The main advantages of ART and the Monte Carlo model for dust exposure assessment are shown in Table 1.

2.2. Measurement of dust concentration in building materials enterprises

In this paper, 15 building materials enterprises in a county in China were investigated, and dust concentrations were measured. Fifteen building materials enterprises are mainly engaged in the processing, manufacturing, and sales of building materials, including sand, cement, concrete and building bricks made from cinder blocks, construction waste, fly ash, sludge, etc. Dust hazards may be found in the fracturing, agitating, and feeding of building materials. All building materials enterprises operate with an 8-hour working day. The main occupational hazard in building materials enterprises is the dust generated during the processing of construction materials.

Dust using the filter membrane weighing method was measured in 5 fracturing, 11 agitating, and 12 feeding segments in 15 building materials enterprises. The measurements obtained by the method do not include chemical fumes, solvents, and gases. Given the confidentiality of the enterprises, the building materials enterprises are represented by serial numbers, as shown in Table 2 and Fig. 1.

2.3. Assessment of the dust exposure

2.3.1. ART

The ART v1.5 used in this paper performs dust exposure assessments based on dust measurements from 15 building materials enterprises, the main steps of which are shown in Fig. 2.

Firstly, the exposure period for each segment is determined. The exposure period is the measured exposure duration of workers to dust, and the remaining time is the non-exposure period.

The exposure scenarios are constructed based on the measured information in each part of the business combined with the factors provided in ART. Seven categories of factors are included: substance emission potential, activity emission potential, localized controls, segregation, dispersion, separation, surface contamination, and fugitive emissions. The specific information is shown in Table 3.

2.3.2. Monte Carlo model

The Monte Carlo model is used in this paper to perform dust exposure assessments of 15 building materials enterprises, the main steps of which are shown in Fig. 3.

Dust exposure assessment for building materials enterprises through the Monte Carlo model requires the establishment of a dust exposure formula. Dust generated by building materials enterprises mainly enters the human body via the respiratory tract [24], and according to “Highlights of The Chinese Exposure Factors Handbook (Adults)” [25] published in 2013, the formula for calculating the average daily exposure dose of hazardous substances (ADD) is specified in Equation (1).

$$ADD = \frac{C \cdot IR \cdot ED \cdot EF \cdot ET}{BW \cdot AT} \tag{1}$$

where:

ADD—average daily exposure dose to dust through breathing, mg/(kg·d); C—concentration of dust, mg/m^3; IR—respiration rate of the worker, m^3/h; ED—exposure duration of the worker in the dust environment, a; EF—exposure frequency of the worker in the dust environment, d/a; ET—continuous exposure time of workers in dusty environments, h/d; BW—body weight of the worker, kg; AT—average exposure time of the worker, d.

By Equation (1), the monitored dust concentrations in the workplace of a building materials enterprise can be converted into the average daily exposure dose of workers to dust through

Table 1
Comparison of ART and the Monte Carlo model advantages

Advantage	ART	The Monte Carlo model
Output	A wide range of outputs can be obtained in the 50th, 75th, 90th, 95th, and 99th percentiles	The output range can be adjusted according to the actual situation
Assessment results	More parameters are required, allowing for more accurate assessment results	Repeatedly calculating a quantity avoids chance in the output and the output is accurate
Other	The exposure assessment results can be corrected by providing the corresponding Bayesian database based on the constructed exposure scenarios	The assessment is based on mathematical statistics, which can be calculated by bringing in formulas, avoiding the influence of subjective factors on the choice of parameters

Table 2
Dust measurements at 15 building materials enterprises

Enterprise	Segment	Exposure duration	Sample (mg/m^3)				Mean	Standard deviation
			1	2	3	4		
1	Fracturing Agitating	4 4	0.37 0.33	0.33 0.33	0.37 0.33	0.33 0.43	0.35 0.36	0.02 0.05
2	Agitating	6	9.43	7.83	0.93	6.27	6.12	3.69
3	Agitating	3	0.10	0.13	0.10	0.13	0.12	0.02
4	Fracturing Agitating Feeding	6 3 3	0.37 0.20 0.20	0.40 0.20 0.20	0.27 0.20 0.20	0.27 0.27 0.50	0.33 0.22 0.28	0.07 0.04 0.15
5	Agitating Feeding	4 4	0.87 1.07	0.13 0.37	0.20 0.77	8.10 0.20	2.33 0.60	3.86 0.39
6	Agitating Feeding	4 4	5.37 1.13	3.77 0.27	6.50 9.67	1.23 7.77	4.22 4.71	2.29 4.71
7	Agitating Feeding	4 4	8.40 8.63	11.30 8.83	19.00 20.90	6.17 14.90	11.22 13.32	5.60 5.83
8	Agitating Feeding	6 4	11.60 21.93	16.37 19.00	4.70 16.07	4.03 7.40	9.72 16.10	5.89 6.27
9	Agitating Feeding	6 5	22.73 6.20	13.57 18.90	6.37 24.67	5.23 19.37	11.98 17.29	8.07 7.84
10	Agitating Feeding	4 4	10.00 13.67	15.23 26.13	15.13 0.97	13.60 6.47	13.49 11.81	2.44 10.87
11	Agitating Feeding	4 6	10.83 10.53	10.20 10.37	11.80 20.20	12.37 10.13	11.30 12.81	0.97 4.93
12	Fracturing Feeding	4 5	1.53 1.30	1.60 1.27	1.73 1.17	1.57 1.20	1.61 1.24	0.87 0.06
13	Fracturing Feeding	6 4	0.83 0.57	0.87 0.60	0.73 0.63	0.77 0.70	0.80 0.63	0.06 0.06
14	Fracturing Feeding	4 4	1.77 2.00	1.87 1.93	2.07 1.80	2.20 1.73	1.98 1.87	0.19 0.12
15	Feeding	4	0.97	1.50	1.23	1.43	1.28	0.24

respiratory exposure. To obtain accurate exposure assessment results, the type of distribution for each factor in equation (1) needs to be determined and then Monte Carlo simulations performed.

For the distribution of dust concentration, the Kolmogorov–Smirnova (K—S test) was applied to the distribution of dust concentration in the workplaces of 15 building materials enterprises using SPSS, and the test results for each group of data were obtained to be greater than 0.05, indicating that the distribution of dust concentration in the workplace should conform to a normal distribution.

For worker respiration rate factors, reference [26] conducted a study of respiration rates in China's population, as shown in Table 4.

According to the situation of 15 building materials enterprises, the workers of the enterprises are all 18—60-year-old males, and the work consists of light physical activity and/or heavy physical activity. Most of the activities are moderate physical activity, combined with Table 4, its factor characteristics are in line with the triangular distribution.

For the continuous exposure time of workers in the dust environment, the exposure duration was determined based on the exposure duration of each segment of the 15 building materials enterprises. The characteristics of the factors are in accordance with the triangular distribution.

For workers' body weight, referring to the recommended information on population weight in the "Highlights of The Chinese

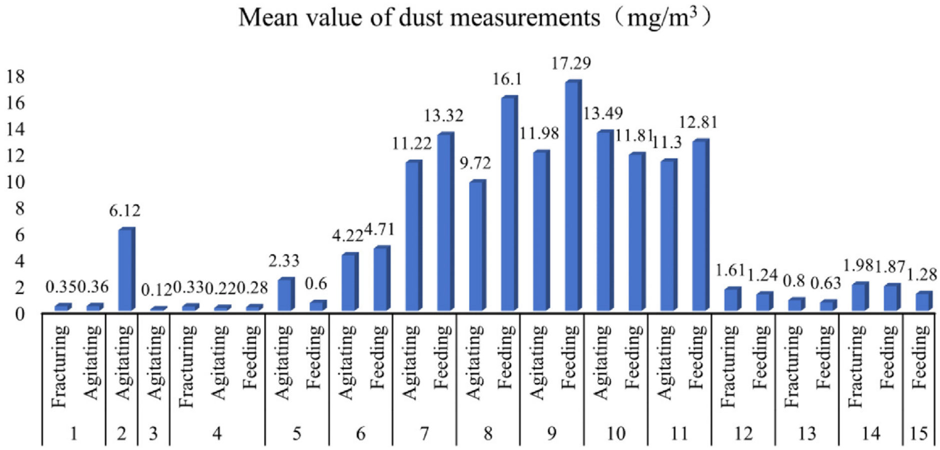

Fig. 1. Mean value of dust measurements at 15 building materials enterprises.

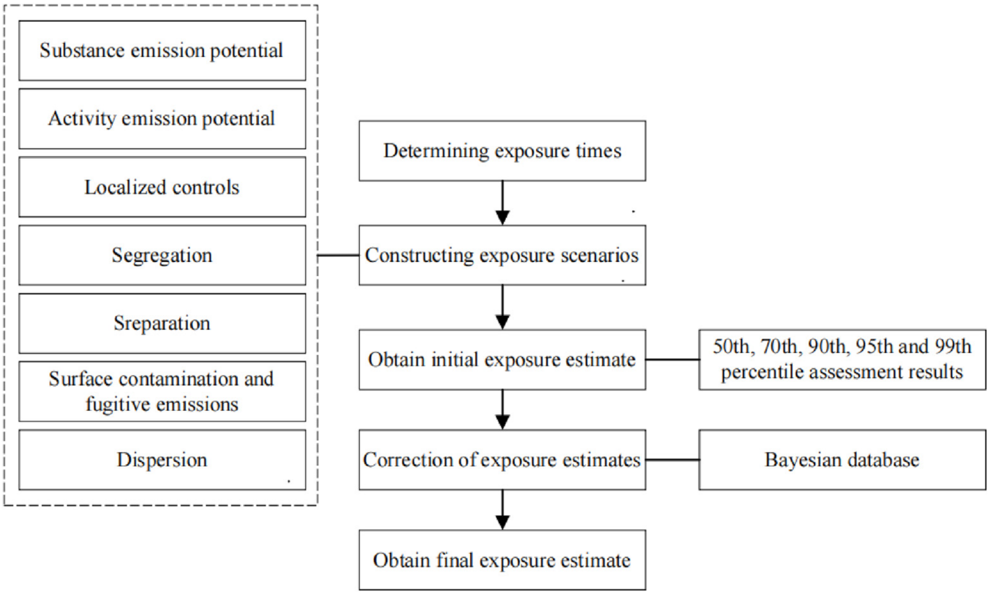

Fig. 2. Steps in dust exposure assessment for ART.

Table 3
Parameter information required to construct the exposure scenarios

Exposure factor		Selection
Potential dust emission	Dustiness	Fine dust, coarse dust, granules and flakes, and firm polymer granules
	Dust moisture content	Drier products (cement, concrete, sludge, and others) Dry products (sand, fly ash, and others)
	Dust weight fraction	10%–50%
Activity emission potential	Fracturing	Fracturing of powder and granular materials Fracturing capacity: 12–2600 tons per hour
	Agitating	Movement and agitation of powders, granules, or pelletized material Agitation volume: 100–1000 kg/min
	Feeding	Transfer of powder, granular, or pelletized material Transfer capacity: 100–1000 kg/min
Other factors	According to the actual research situation in building materials enterprises	

*Determination of the dust weight fraction was made with reference [23].

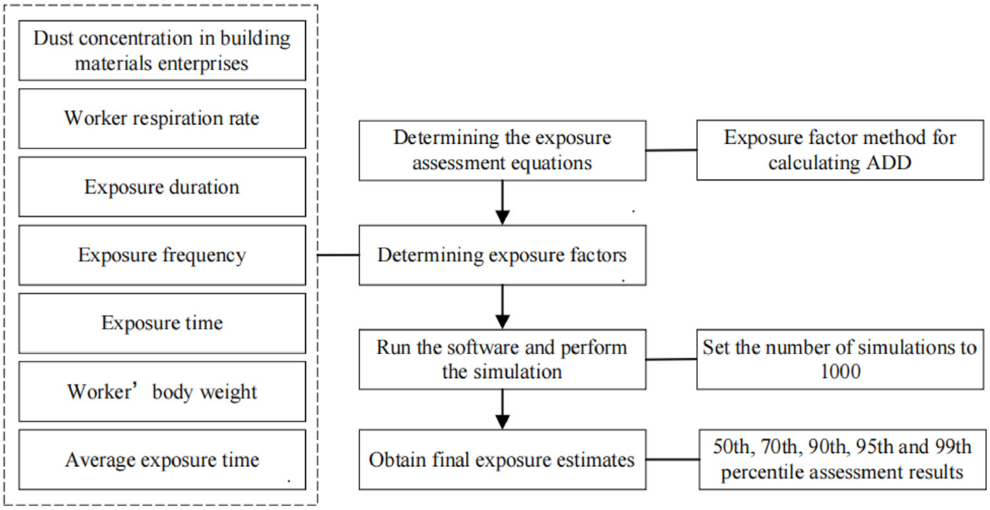

Fig. 3. Steps in dust exposure assessment for the Monte Carlo model.

Table 4
Respiration rates appropriate to the characteristics of the Chinese population

Age/Years	Gender	Respiration rate at different activity intensities (m^3/h)					
		Resting	Sitting	Light physical activity	Moderate physical activity	Heavy physical activity	Extremely heavy physical activity
18–60	Male	0.48	0.57	0.95	1.90	2.85	4.75
	Female	0.35	0.43	0.71	1.42	2.13	3.54

Table 5
Recommended body weight of Chinese population

Age group		Body weight (kg)		
		Total	Male	Female
By age group	18–44 years old	60.1	65.3	55.6
	45–59 years old	62.4	66.0	59.5
	60–79 years old	59.4	62.4	56.6

Exposure Factors Handbook (Adults)" published by China in 2013, as shown in Table 5, we found that the body weight factors of the employees conformed to the characteristics of a normal distribution.

For the exposure frequency and exposure duration, according to references [27,28] on the situation of residents in China, the distribution was obtained conforming to the triangular distribution. The average exposure duration in this study was consistent with the exposure duration, expressed as exposure duration × 365, in line with the characteristics of a uniform distribution.

In summary, the values and distribution of each factor were obtained as shown in Table 6.

2.4. Comparative study of the application of ART and Monte Carlo

2.4.1. Comparative analysis of exposure assessment results

The results of ART and the Monte Carlo model were compared and analyzed for the assessment of dust exposure in fracturing, agitating, and feeding at 15 building materials enterprises. The results of the two models were unified in the following 3 steps.

(1) Unit conversion of ART assessment results: The ART assessment results are multiplied by the area range of worker activity to obtain the total dust exposure dose in mg.
(2) Unit conversion of Monte Carlo model assessment results: The Monte Carlo model assessment results are multiplied by the total body weight of workers in the area of activity to obtain the total average daily dust exposure dose. The unit is mg/d.
(3) Based on step (2), the Monte Carlo model assessment results are multiplied by one working day to express the total amount of dust exposure in mg for each segment.

After the above three steps, the unit unification of the assessment results of the two models was completed. To determine whether different segments have an impact on the assessment of the two models, the dust exposure assessment results of the two models for the fracturing, agitating, and feeding segments of 15 building materials enterprises were compared.

2.4.2. Comparative study of dust exposure assessment factors

For ART, the factors need to be quantified. In this paper, the factors are quantified based on the scoring of ART for each factor [29] and assigned a uniform value according to a scale of 1 to 5. For example, 1 for the respirable fraction of the product ≤100 mg/kg, 5 for the respirable fraction of the product >5000 mg/kg. Monte Carlo simulations are quantitative assessment methods that allow the measured factors to be analyzed directly.

In this paper, the Pearson coefficient, which is the most commonly used correlation indicator, is used, and the closer it is to 1 or −1, the better the correlation [30]. Typically, Pearson coefficients between 0.8 and 1.0 are very strong correlations, 0.6 and 0.8 are strong correlations, 0.4 and 0.6 are moderate correlations, 0.2 and 0.4 are weak correlations, and 0 and 0.2 are very weak or no correlations.

3. Results

3.1. ART exposure assessment results and Bayesian correction

ART was run to initially obtain the dust exposure concentrations at the 50th, 75th, 90th, 95th, and 99th percentiles for each link of the 15 building materials enterprises. The Bayesian exposure data library in the ART was used to correct and the exposure assessment results for each segment of the 15 building material enterprises were obtained as shown in Table 7.

Based on the above results, combined with the dust exposure assessment results, ART tends to underestimate exposure assessment results, and the 99th percentile exposure assessments of ART are more accurate than dust measurements.

3.2. Monte Carlo exposure assessment results

The information for each factor in Table 5 was brought into Equation (1) and input into Crystal Ball for Monte Carlo simulation, setting the number of simulations to 1000 and the output to be consistent with ART and setting the output to the 50th, 75th, 90th, 95th, and 99th percentiles of dust exposure assessment, as shown in Table 8.

Table 6
Exposure factor values and factor distributions

Exposure factor	Symbol	Unit	Mean	Standard deviation	Most p robable v alue	Minimum value	Maximum value	Distribution
Respiration rate	IR	m^3/h	—	—	1.9	0.95	2.85	Triangular distribution
Body weight	BW	kg	69.5	5.8	—	—	—	Normal distribution
Exposure duration	ED	a	—	—	11	3	17	Triangular distribution
Exposure frequency	EF	d/a	—	—	292	249	365	Triangular distribution
Average exposure time	AT	d	—	—	—	1095	6205	Uniform distribution

Table 7
Statistical results of dust exposure assessment by ART for 15 enterprises

Enterprise	Testing segment	Exposure dose and interval by percentiles (mg/m^3)				
		50th	75th	90th	95th	99th
1	Fracturing	0.01	0.03	0.05	0.07	0.14
	Agitating	0.02	0.05	0.14	0.22	0.43
2	Agitating	0.35	0.84	1.30	1.70	2.80
3	Agitating	0.02	0.04	0.07	0.10	0.12
4	Fracturing	0.02	0.041	0.08	0.11	0.22
	Agitating	0.01	0.05	0.07	0.10	0.19
	Feeding	0.02	0.04	0.07	0.10	0.19
5	Agitating	0.12	0.24	0.31	0.57	1.70
	Feeding	0.02	0.05	0.09	0.13	0.26
6	Agitating	0.27	0.57	1.10	1.50	2.80
	Feeding	0.27	0.57	1.00	2.00	3.00
7	Agitating	0.52	1.10	2.30	3.50	7.60
	Feeding	0.60	1.10	2.00	2.90	5.60
8	Agitating	0.53	1.00	1.90	2.80	5.60
	Feeding	1.00	1.80	3.10	4.30	8.00
9	Agitating	0.60	1.30	2.60	3.90	8.40
	Feeding	1.50	2.40	3.80	4.90	8.20
10	Agitating	0.61	1.20	2.20	3.20	6.20
	Feeding	0.63	1.30	2.50	3.70	7.60
11	Agitating	0.54	1.10	2.00	2.90	5.80
	Feeding	0.69	1.30	2.40	3.40	6.70
12	Fracturing	0.06	0.13	0.25	0.36	0.70
	Feeding	0.08	0.14	0.24	0.32	0.56
13	Fracturing	0.04	0.09	0.15	0.21	0.41
	Feeding	0.04	0.08	0.15	0.21	0.41
14	Fracturing	0.09	0.19	0.35	0.51	0.99
	Feeding	0.05	0.16	0.26	0.35	0.58
15	Feeding	010	0.17	0.26	0.35	0.58

Based on the above results, combined with the dust exposure assessment results, the Monte Carlo tends to underestimate exposure assessment results, and the 99th percentile exposure assessments of the Monte Carlo are more accurate than dust measurements, which is consistent with the ART assessment results, indicating that both models have more reliable assessment results.

3.3. *Comparative study results*

3.3.1. *Comparative analysis of exposure assessment results*

The results of the ART and Monte Carlo model dust exposure assessment comparison are shown in Figs. 4–6. The solid lines represent the results of ART, and the dashed lines represent the results of the Monte Carlo model. The results are shown in five colors for each of the five percentile results.

By comparing the two models, similarities and differences can be obtained in the assessment of dust exposure for building materials enterprises.

(1) Similarity

These two models had the highest coincidence of assessment results at the 75th percentile. Furthermore, in the Monte Carlo model assessment results, the dust exposure dose was mainly concentrated around the 75th percentile, so the 75th percentile data were chosen for further analysis in this study.

(2) Difference

1) Individual assessment results vary widely. Dust exposure assessments by the Monte Carlo model are susceptible when there are large differences in sample data, such as in enterprise 9, where the 95th and 99th percentiles are particularly pronounced in the agitating and feeding segments, while ART yields flatter results.
2) The ART assessment results were lower than the Monte Carlo model assessment results. As can be seen in Fig. 3, for the fracturing segment, the ART results are smaller than the Monte Carlo model results, which is consistent with the results

Table 8
Statistical results of dust exposure assessment by the Monte Carlo model for 15 enterprises

Enterprise	Testing segment	Average daily exposure concentration of dust by percentiles (mg/(kg·d))				
		50th	75th	90th	95th	99th
1	Fracturing	0.03	0.05	0.08	0.11	0.17
	Agitating	0.03	0.05	0.08	0.11	0.17
2	Agitating	0.45	0.83	1.47	2.06	3.83
3	Agitating	0.01	0.02	0.03	0.04	0.06
4	Fracturing	0.03	0.06	0.09	0.12	0.18
	Agitating	0.02	0.04	0.06	0.08	0.12
	Feeding	0.02	0.04	0.08	0.10	0.19
5	Agitating	0.11	0.28	0.59	0.94	1.90
	Feeding	0.04	0.08	0.15	0.20	0.33
6	Agitating	0.32	0.61	1.08	1.56	2.95
	Feeding	0.29	0.62	1.28	1.96	3.94
7	Agitating	0.88	1.61	2.76	3.90	7.13
	Feeding	1.12	1.87	3.16	4.26	7.49
8	Agitating	0.66	1.35	2.45	3.33	6.52
	Feeding	1.20	2.28	3.90	5.25	9.31
9	Agitating	0.71	1.43	2.79	4.22	7.12
	Feeding	1.38	2.39	4.53	5.77	9.70
10	Agitating	1.11	1.91	3.09	4.00	6.40
	Feeding	0.93	1.83	3.48	4.87	9.54
11	Agitating	1.03	1.66	2.68	3.05	5.59
	Feeding	1.12	1.90	3.16	4.00	7.14
12	Fracturing	0.12	0.23	0.42	0.55	0.98
	Feeding	0.11	0.18	0.29	0.39	0.61
13	Fracturing	0.08	0.14	0.21	0.27	0.41
	Feeding	0.06	0.11	0.17	0.22	0.34
14	Fracturing	0.17	0.28	0.45	0.61	0.94
	Feeding	0.16	0.26	0.42	0.55	0.88
15	Feeding	0.11	0.19	0.29	0.42	0.64

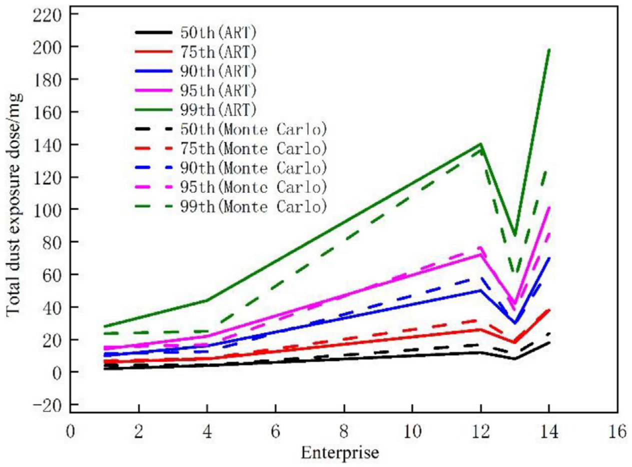

Fig. 4. Comparison of dust exposure assessment results for the fracturing segment.

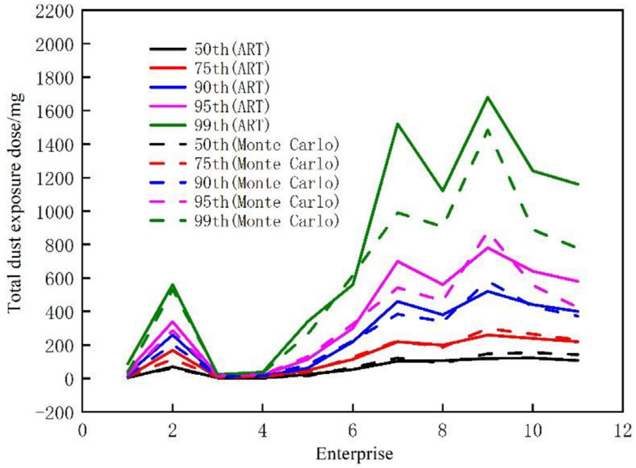

Fig. 5. Comparison of dust exposure assessment results for the agitating segment.

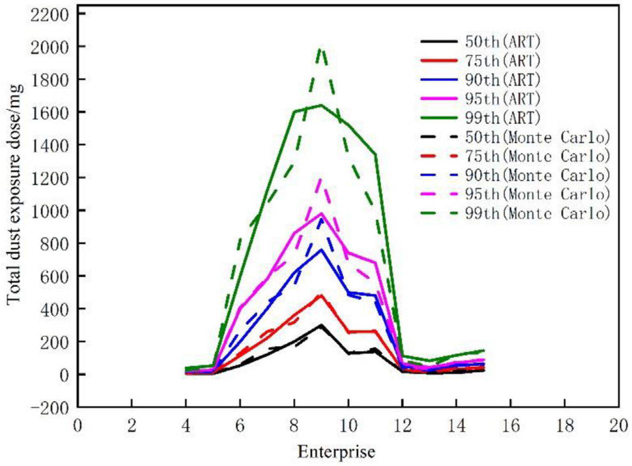

Fig. 6. Comparison of dust exposure assessment results for the feeding segment.

obtained by Donnell [31]. However, in the assessment results for the agitating and feeding segments, there were cases of overestimation of ART assessment results in individual building materials enterprise segments.

3.3.2. *Comparative study of dust exposure assessment factors*

This section used correlation analysis to investigate the relevant factors of the two models and the results are shown in Tables 9 and 10.

According to Tables 9 and 10, ART and the Monte Carlo model for assessing dust exposure in building materials enterprises are influenced by different factors.

The results of the dust exposure assessment for building materials enterprises by ART are strongly influenced by four categories of factors: localized controls, segregation, dispersion, surface contamination, and fugitive emissions, with the results of the dust exposure assessment for fracturing, agitating, and feeding all being very strongly correlated with these four types of factors.

For the dust exposure assessment for building material enterprises by the Monte Carlo model, the results obtained are strongly influenced by dust concentration and duration of exposure, with the results of dust exposure assessment for fracturing, agitating, and feeding all being extremely strongly correlated with these two types of factors.

4. Discussion

Combined with the dust exposure assessment results, ART tends to underestimate exposure assessment results. The factors provided by ART will be more similar when the dust concentration is low in each part of the building materials enterprises, which is not conducive to the construction of exposure scenarios and will have an impact on the assessment results, such as the agitating segment of enterprise 5 versus the feeding segment of enterprises 12, 13, and 15. Combined with previous studies, ART tends to overestimate lower exposures and underestimate higher exposures [32], yielding it is suitable for scenarios with high dust concentrations in building materials enterprises, and more accurate and stable when the average dust concentration in the workplace is greater than 6 mg/m^3. The Monte Carlo model is suitable for scenarios with low dust concentrations in building materials enterprises and is more accurate and stable when the average dust concentration in the workplace is less than 1.5 mg/m^3. The dust concentration at each sampling point may be unevenly distributed when the dust concentration is high in each part of the building materials enterprises, and the assessment results will also be affected, such as the agitating segment of enterprises 2 and 8 versus the feeding part of enterprises 8 and 10.

The dust exposure assessment of building materials enterprises by ART is mainly influenced by localized controls, segregation, dispersion, surface contamination, and fugitive emissions. Previous studies have identified the most important and influential factors are localized controls and substance emission potential [33]. Considering the different exposure scenarios studied, both yielded that localized controls are one of the most important factors influencing the ART exposure assessment, which deserves to be validated in further studies. Dust exposure assessment for building materials enterprises by the Monte Carlo model is most significantly influenced by dust concentration. The dust concentration at each sampling point may be unevenly distributed when the dust

Table 9
Correlation analysis of ART assessment results

ART factor		Exposure duration	Dustiness	Moisture content	Weight fraction	Substance emission potential	Activity emission potential
Correlation coefficient	Fracturing segment	0.883	−0.883	−0.841	—	−0.841	—
	Agitating segment	0.670	−0.557	−0.901	—	−0.901	—
	Feeding segment	0.558	−0.566	−0.886	—	−0.685	—
ART factor		Localized controls	Segregation	Dispersion	Separation	Surface contamination and fugitive emission	Localized controls
Correlation coefficient	Fracturing segment	−0.975	−0.883	−0.841	−0.883	−0.938	Fracturing segment
	Agitating segment	−0.930	−0.898	−0.896	−0.773	−0.899	Agitating segment
	Feeding segment	−0.923	−0.833	−0.855	−0.821	−0.867	Feeding segment

Table 10
Correlation analysis of the Monte Carlo model assessment results

The Monte Carlo model factor		Dust concentration	Respiration rate	Exposure duration	Exposure frequency	Continuous exposure time	Average exposure duration
Correlation coefficient	Fracturing segment	0.899	0.838	0.854	0.877	0.428	−0.869
	Agitating segment	0.980	0.661	0.877	0.664	0.515	−0.862
	Feeding segment	0.970	0.713	0.891	0.774	0.463	−0.710

concentration is high in each segment of the building materials enterprises, and the assessment results will also be affected, such as the agitating segment of enterprises 2 and 8 versus the feeding segment of enterprises 8 and 10.

5. Conclusion

ART is suitable for scenarios where the workplace information is specific and the average dust concentration is greater than or equal to 1.5 mg/m^3. The Monte Carlo model is suitable for scenarios where the dust concentration in the workplace is more homogeneous and the average dust concentration is less than or equal to 6 mg/m^3. It is recommended that for dust assessment in building materials enterprises, ART is used if the dust concentration is greater than or equal to 1.5 mg/m^3, Monte Carlo is used if it is greater than or equal to 6 mg/m^3, and both models can be used if it is between 1.5 and 6 mg/m^3. Building materials enterprises can control the hazards of dust exposure to workers by conducting regular and effective dust exposure assessments. Based on the results of the dust exposure assessment, building materials enterprises can also adjust dust control measures promptly, especially for workplaces with high dust concentrations, and take timely measures to control them.

There are limitations in this study, as only 15 building materials enterprises were selected for analysis, which is a small sample for the study, and the sample could be expanded in the future to validate the results of this study to avoid the chance of the finding. In the future, ART and Monte Carlo can also be used to assess the exposure of other types of enterprises or other substances to enrich the applicability of the model through comparative studies.

Conflicts of interest

The authors report there are no competing interests to declare.

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Data availability statement

All data that the finding of this study are included in this manuscript and its supplementary information files.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.shaw.2023.12.003.

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