

Application of Event Tree Analysis and Analytic Hierarchy Process for Assessing the Risk of Formaldehyde Exposure in the Process of Grinding Wheel

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Abstract

Risk assessment is of paramount important in industrial plants due to the nature of work. There are many risk assessment methods used in industrial plants. However, it does not suggest a specific approach on how to assess the risks. Therefore, the purpose of this cross-sectional study was to integrate the event tree analysis (ETA) and analytic hierarchy process for assessing the risk of formaldehyde exposure in the process of grinding wheel. A cross-sectional study was conducted in June - August, 2020. An analytic hierarchy process by Expert Choice V.11 was used a tool for determining relative weight of probability of measures to prevent exposure to formaldehyde concentration in the air. RAM Commander V.8.6 was then used to assess risk from event tree structure with consideration of the probability and impact of the risks. The findings revealed that improper working layout in combination with inappropriate wearing respiratory protective devices to reduce exposure to formaldehyde were a high level of risk and improper general exhaust ventilation, improper working layout in combination with inappropriate wearing respiratory protective devices to reduce exposure to formaldehyde were a moderate risk. The company board and management should include potential failures of measures to prevent exposure to formaldehyde and actions to be taken to prevent exposure to formaldehyde in order to efficiently address the risks that are likely to arise from routine operational procedures.

Keywords: Event tree analysis, Analytic hierarchy process, Risk assessment, Formaldehyde, Grinding wheel

Introduction

Formaldehyde is a raw material for many industrial products. Formaldehyde from the manufacturing plant is in form of formalin, which is used as a raw material for the production of urea-formaldehyde (UF), phenol-formaldehyde resins, melamine formaldehyde (also called melamine or MF), polyacetal, also commonly known as acetal or polyoxymethylene (POM) and other chemicals. Although formaldehyde has many uses in industry, it is considered a highly hazardous chemical in terms of safety and health. Formaldehyde is classified as a Category 1 carcinogen (a human carcinogen) by the International Agency for Research on Cancer (IARC) [1] and can cause nasopharyngeal carcinoma and leukemia. Several studies have been conducted to study the effects of formaldehyde on health, such as Dangruang [2] studies on the health impact assessment of workers from formaldehyde exposure: Melamine faced board processing. Formaldehyde concentration in air was collected and assessing the risk of cancer, it was found that the risk value exceeded an acceptable value of the United States Environmental Protection Agency (U.S. EPA). For example, Tongsuntia and Chaiklieng [3] conducted a study on health risk assessment of formaldehyde exposure among medical laboratory personnel; it was found that the most personnel were at a very high risk. Boonyayothin *et al.* [4] conducted a study on cancer risk assessment of formaldehyde exposure via inhalation among autopsy staffs. The mean cancer risk is unacceptable level according to U.S. EPA recommendation. Liang *et al.* [5] conducted a study of formaldehyde exposure in indoor air from public places and its associated health risks in Kunshan City, China. The carcinogenic risk of formaldehyde for employees of the 4 categories of public places was 4.70×10^{-5} to 1.57×10^{-4} , which was greater than the acceptable carcinogenic risk probability (1×10^{-6}) from the U.S. EPA. The highest carcinogenic risk occurred in bathing and beauty places, and male employee carcinogenic risk was greater than that of females. Saowakon *et al.* [6] conducted a study of

formaldehyde exposure in gross anatomy laboratory of Suranaree University of Technology: A comparison of area and personal sampling. All the personal exposure data obtained exceeded the threshold limit of National Institute for Occupational Safety and Health (NIOSH) [7] and World Health Organization (WHO) agencies [8]. Huang *et al.* [9] found that indoor formaldehyde concentrations of 85 % dwellings and 67 % offices were above the acute Reference Exposure Level (REL) recommended by the California Office of Environmental Health Hazard Assessment (OEHHA) [10] and the concentrations of all tested buildings were above the chronic REL recommended by the OEHHA. The median cancer risks from indoor exposure to formaldehyde was 1,150 and 106 per million (based on U.S. EPA IRIS IURs) [11] and Chang *et al.* [12] also conducted to study an evaluation of indoor air pollution during the decorating process and inhalation health risks in Xi'an, China. It was found that the formaldehyde and Volatile Organic Compounds (VOCs) concentrations were measured in 200 other rooms decorated within a 2-year period in Xi'an, and the results indicated that wallpapering, wooden flooring and furniture were the major decorating processes emitting these compounds. In addition, a health risk assessment of the monitored formaldehyde and VOCs in the rooms 1 year after decorating showed that benzene posed the greatest health risk among the assessed VOCs. It obviously can be seen that there is still a lack of good preventive measures against formaldehyde exposure. This is an important thing to ensure the safety of employees at work. Assessing the risk of control and prevention measures to prevent formaldehyde exposure is important in occupational health and safety. Therefore, this research aimed to study measures to prevent formaldehyde exposure. Including applying the risk assessment technique using the ETA method, which is a hazard identification technique to analyze and assess the impact that will occur continuously when an initiating event occurs. It is a forward-thinking idea to analyze the consequences that can occur when a machine, equipment is damaged or someone malfunctions, so that it is known how it happened and how likely it is. This technique is decision analysis and therefore appropriate and consistent with the task of applying it for risk assessment as compared to other techniques. However, the ETA has limitations in determining the reliability of the equipment and the probability of the event, which sometimes some equipment or measures are unable to determine these values. Therefore, it is necessary to apply other techniques to determine the reliability and probability of events. The Analytic Hierarchy Process (AHP) proposed by Saaty [13] is a versatile tool for dealing with complex decision-making problems. It is a hierarchical structure of goals, objectives, main criteria, sub-criteria and alternative. The AHP helps decision makers find one the best suits for their goal and their understanding of the problem. It provides a comprehensive and rational framework for structuring a decision problem, for representing and quantifying its elements, for relating those elements to overall goals, and for evaluating alternative solutions. This research eventually has applied an AHP to determine the relative weight of each situation from an ETA diagram and to determine the risk of exposure to formaldehyde in the process of grinding wheel. It also proposed measures to prevent exposure to formaldehyde.

Materials and methods

Study design and setting

A cross-sectional study was conducted between June and August 2020 in the process of grinding wheel in one of Rojana Industrial Park in Phra Nakhon Si Ayutthaya Province, Thailand. The study area was a process of grinding wheel. This process of grinding wheel room is recirculation air ventilation as shown in **Figure 1**. In this study, the grinding wheel process was selected by considering the prioritization of occupational health and safety problems, namely attention to problem of workers, attention of management to problem solving and problem size (139 workers were exposed to formaldehyde concentration in the air, which was the most employed process out of all processes, and this process had a formaldehyde concentration in the air that exceeded an acceptable value of the Thai law).

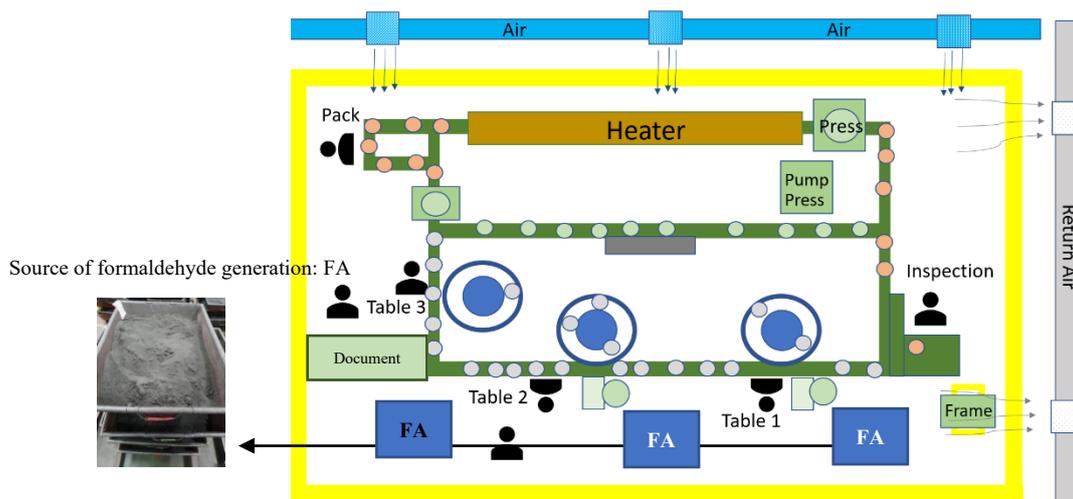


Figure 1 Grinding wheel study room.

Instrument development

An instrument for data collection consisted of RAM Commander’s ETA Version 8.6 for creating an ETA structure and using Expert Choice V.11 in computing the relative weight from an AHP structure and to determine the risk of exposure to formaldehyde in the process of grinding wheel.

RAM Commander is the pioneering Reliability and Safety software for reliability professionals and design engineers, developed by the ALD Reliability and Safety Solutions. RAM Commander combines ingenuity of approach, calculation accuracy and convenience of use. Designed by reliability engineers, RAM Commander covers the entire scope of engineering tasks related to reliability of electronic, electro-mechanical and mechanical systems. RAM Commander (Reliability, Availability, Maintainability Prediction and Analysis) is a 32-bit integrated LAN-compatible Windows software package for reliability, availability, and maintainability prediction, failure modes and effects criticality analysis (FMECA), testability analysis, process and design, and safety analysis by using Fault Tree Analysis (FTA), ETA, Markov Chains Analysis, and Process Hazard Analysis (PHA). This research uses this tool to create an ETA diagram. ETA is one of the most widely used methods in system risk analysis. It is an inductive failure analysis performed to determine the consequences of single failure for the overall system risk or reliability. ETA uses similar logic and mathematics as FTA, but the approach is different - FTA uses deductive approach (from system failure to it is reasons) and ETA uses the inductive approach (from basic failure to it is consequences).

The AHP method provides a structured framework as shown in **Figure 2** for setting priorities on each level of the hierarchy using pairwise comparisons that are quantified using 1 - 9 scale in **Table 1**. The pairwise comparisons between the *m* decision criteria can be conducted by asking occupational health and safety experts’ questions. The answers to these questions form an *m* × *m* pairwise comparison matrix which is defined as follows in Eq. (1).

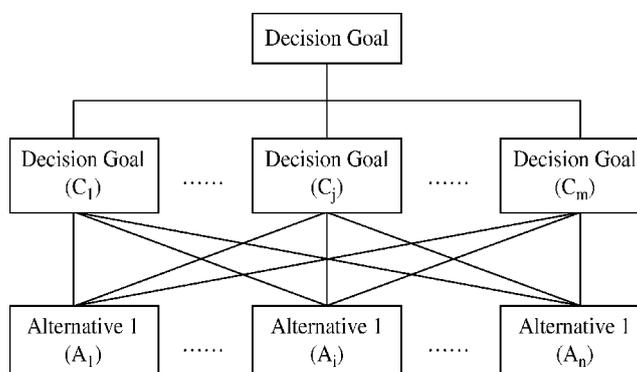


Figure 2 Hierarchy for a typical 3-level multiple criteria decision-making problem.

Table 1 Nine-point pairwise comparison scale [13].

Numerical value	Verbal meaning for risk factor evaluation
1	Equally important
2	Equally to moderately more important
3	Moderately more important
4	Moderately to strongly more important
5	Strongly more important
6	Strongly to very strongly more important
7	Very strongly more important
8	Very strongly to extremely more important
9	Extremely more important

$$A = (a_{ij})_{m \times m} = \begin{matrix} C_1 & \begin{bmatrix} a_{11} & a_{12} & \dots & a_{1m} \\ a_{21} & a_{22} & \dots & a_{2m} \\ \vdots & \vdots & \dots & \vdots \\ a_{m1} & a_{m2} & \dots & a_{mn} \end{bmatrix} \\ C_2 & \\ \vdots & \\ C_m & \end{matrix} \tag{1}$$

Where a_{ij} represents a quantified judgment on w_i/w_j with $a_{ii} = 1$ and $a_{ij} = 1/a_{ji}$ for $i, j = 1, \dots, m$. If the pairwise comparison matrix $A = (a_{ij})_{m \times m}$ satisfies $a_{ij} = a_{ik} a_{kj}$ for any $i, j, k = 1, \dots, m$, then A is said to be perfectly consistent; otherwise it is said to be inconsistent. Form the pairwise comparison matrix A , the weight vector W can be determined by solving the following characteristic Eq. (2).

$$AW = \lambda_{\max} W \tag{2}$$

Where λ_{\max} is the maximum eigenvalue of A . The expert question may be unable to provide perfectly consistent pairwise comparisons, it is demanded that the pairwise comparison matrix A should have an acceptable consistency, which can be checked by the following consistency ratio ($C.R.$), as shown in Eq. (3).

$$C.R. = \frac{(\lambda_{\max} - n)/(n-1)}{RI} \tag{3}$$

Where RI is a random inconsistency index, whose value varies with the order of pairwise comparison matrix. **Table 2** shows the RI values for the pairwise comparison matrices with the order from 1 to 10. If $C.R. \leq 0.1$, the pairwise comparison matrix is thought to have an acceptable consistency; otherwise, it need to be revised.

Table 2 Random inconsistency index for pairwise comparison matrices with the order from 1 - 10 [13].

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

Decision alternatives can be compared pairwise with respect to each decision criterion in the same way. After the weights of decision criteria and the weights of decision alternatives with respect to each criterion are obtained by using pairwise comparison matrices, the overall weight of each decision alternative with respect to the decision goal can be generated by using the following simple additive weighting method [13], as shown in Eq. (4).

$$w_{Ai} = \sum_{j=1}^m w_{ij} w_j, i = 1, \dots, n, \tag{4}$$

Where w_j ($j = 1, \dots, m$) are the weights of decision criteria, w_{ij} ($i = 1, \dots, n$) are the weights of decision alternatives with respect to criterion j , and w_{Ai} ($i = 1, \dots, n$) are the overall weights of decision alternatives. The best decision alternative will be the one with the biggest overall weight with respect to the decision goal.

Expert Choice is decision-making software that is based on multi-criteria decision making. Expert Choice implements the AHP was used for computing the relative weight instead of calculating by hand according to Eqs. (1) to (4).

Order of operations steps

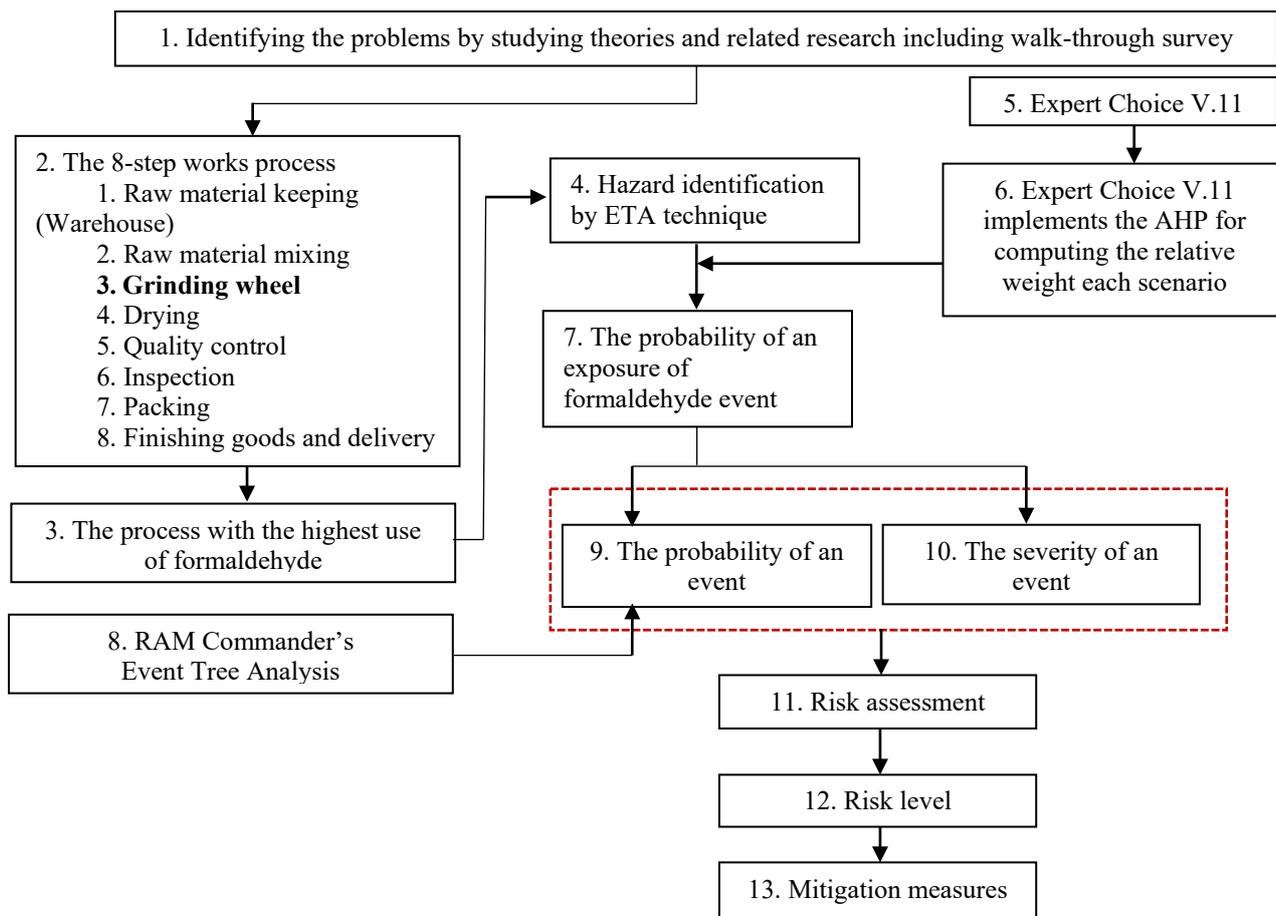


Figure 3 Order of operation steps.

The research process involves identifying the problems by studying theories and related research including walk-through survey all processes (The 8-step works process for grinding wheel production) in the factory, the process with the highest use of formaldehyde was identified the hazards by ETA technique and use Expert Choice V.11 implements the AHP for computing the relative weight each scenario then the probability of an exposure of formaldehyde event was obtained. Assessing the risk of formaldehyde exposure is considered into 2 components: Probability and severity of an exposure of formaldehyde event. The probability of an exposure of formaldehyde event can be calculated by the RAM Commander’s ETA software. An order of operation steps was shown in **Figure 3**.

Table 3 Probability level and meaning [14].

Score	Probability	Likelihood
5	Very likely	More than 80 %
4	Significant chance	51 - 80 %
3	Moderately likely	31 - 50 %
2	Possible but not likely	11 - 30 %
1	Negligible likelihood of occurrence/remote possibly	Less than 10 %

RAM Commander’s ETA software was used for calculating the probability of an exposure of formaldehyde event. The likelihood results are equal to less than 10, 11 - 30, 31 - 50, 51 - 80, and more than 80 %, meaning that the probability level is negligible likelihood of occurrence/remote possibly (Score = 1), possible but not likely (Score = 2), moderately likely (Score = 3), significant chance (Score = 4) and very likely (Score = 5), respectively.

Table 4 Severity and definitions [15].

Score	Severity	Description
1	Insignificant	Incident not resulting in injury (i.e. near miss)
2	Minor	Minor injury or illness, 1 st aid treatment needed
3	Moderate	Major injury requiring medical attention and/or causing > 3days absence
4	Significant	Single major injury or number of major injuries, or long-term incapacity/disability (loss of limb)
5	Major	Death or major permanent incapacity

The details of the severity can be described as incident not resulting in injury (i.e. near miss), meaning that the severity is insignificant (Score = 1), minor injury or illness, 1st aid treatment needed means that the severity is minor (Score = 2), major injury requiring medical attention and/or causing > 3 days absence means that the severity is moderate (Score = 3), single major injury or number of major injuries, or long term incapacity/disability (loss of limb) means that the severity is significant (Score = 4). Lastly, death or major permanent incapacity means that the severity is major (Score = 5).

Table 5 Risk assessment matrix [14].

Risk Assessment Matrix			Probability				
			Negligible likelihood of occurrence/remote possibly	Possible but not likely	Moderately likely	Significant chance	Very likely
			1	2	3	4	5
Impact/ Severity	Major	5	5	10	15	20	25
	Significant	4	4	8	12	16	20
	Moderate	3	3	6	9	12	15
	Minor	2	2	4	6	8	10
	Insignificant	1	1	2	3	4	5
			Risk level				

The level of probability and severity of an exposure of formaldehyde event from **Tables 3** and **4**, a risk assessment is performed in **Table 5** and unacceptable risk level (Score = 20 - 25) including high risk level (Score = 15 - 19) requires further mitigation measures.

Results and discussion

Formaldehyde was highly used in the process of molding grinding wheel. In this process, there were measures to prevent formaldehyde exposure, namely there was the general exhaust ventilation, appropriate working layout, wearing respiratory protective devices to reduce exposure to formaldehyde, and the life expectancy of respiratory protection equipment. Expert Choice V.11 implements the AHP for computing the relative weight each scenario as shown in **Figures 4 and 5** and **Table 6**. Similarly, Hyun *et al.* [14], Petruni *et al.* [16], Kokangül *et al.* [17] and Garbuzova-Schlifter and Madlener [18] they were applied the AHP for calculating the relative weight for their decision goal. For this research have applied an AHP to determine the relative weight of each situation from an ETA diagram and to determine the risk of exposure to formaldehyde in the process of grinding wheel. This is the 1st application of AHP with ETA. No other research has been found to apply, but most of them would find applications of AHP to FTA techniques. However, the reliability of the information has been conducted through extensive research and expert judgments to gain the relative weight of measures to prevent exposure to formaldehyde. As a result of the likelihood or probability of occurrence is even more clearly defined without having to make sense of risk assessment. In addition, Akyuz *et al.* [19] also applied the fuzzy logic to fault tree and ETA of the risk for cargo liquefaction on board ship. This research is very similar to this one, but the technique used was complex and difficult to practice for the general public. The risk assessor must have specialized knowledge of fuzzy logic, but the results of the risk assessment will be more accurate. However, the results of risk assessments using AHP and Fuzzy logic techniques were not very different. Therefore, it is easy to assess the risk. AHP technique is also suitable for the application. Finally, Rosqvist *et al.* [20] also found that ETA is a technique that can be applied for flood protection. This is similar to this research that has been applied ETA technique for assessing the risk of measures to prevent exposure to formaldehyde. However, there are differences between these 2 studies: The implementation of AHP was used to make decisions for determining the relative weight for reducing bias assessments (subjective probability).

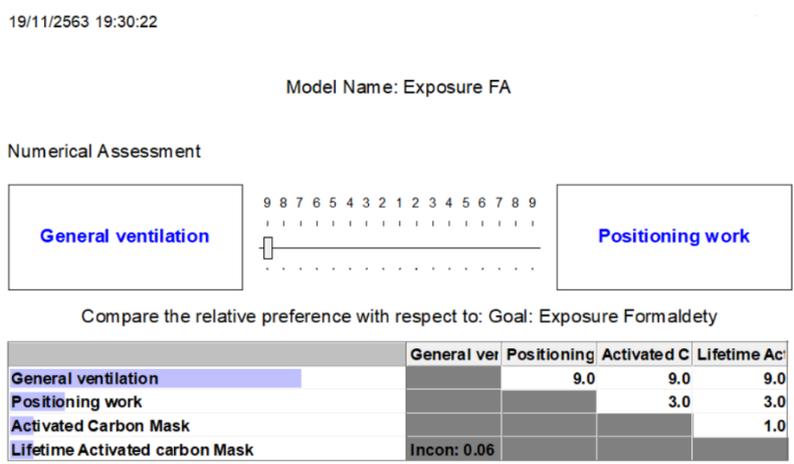


Figure 4 Pairwise comparisons of formaldehyde exposure assessment in Expert Choice V.11 program.

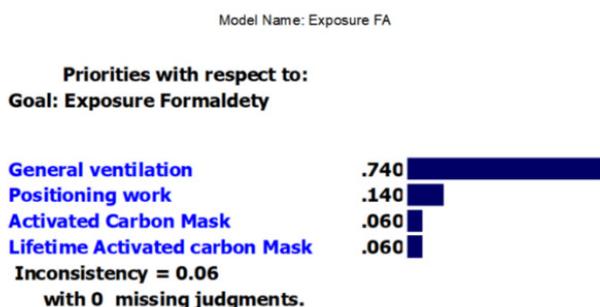


Figure 5 Relative weight calculation using Expert Choice V.11 program.

Table 6 Relative weight of preventive measures for exposure to formaldehyde in the process of grinding wheel.

Preventive measures for exposure to formaldehyde	Relative weight
1) General exhaust ventilation	0.740
2) Appropriate working layout	0.140
3) Wearing respiratory protective devices to reduce exposure to formaldehyde	0.060
4) Life expectancy of respiratory protection equipment	0.060

The probability of an exposure of formaldehyde event can be calculated by the RAM Commander’s ETA software and consider the probability of formaldehyde exposure as shown in **Figure 6** then assessing the risk of formaldehyde exposure in the process of grinding wheel. The results of risk assessment were revealed in **Table 7**.

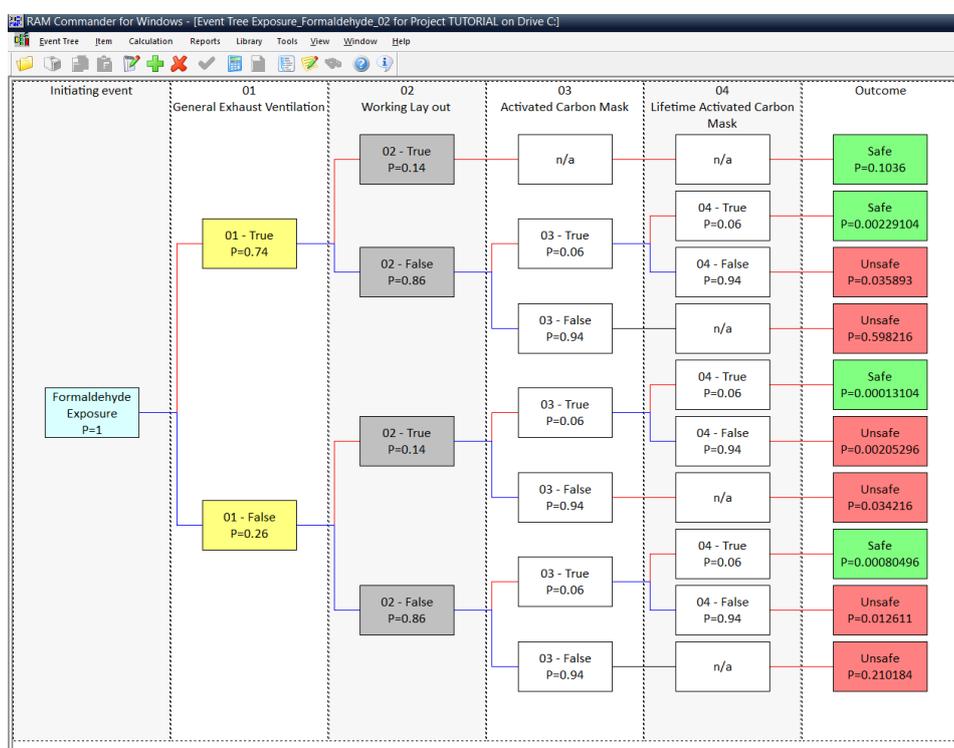


Figure 6 RAM Commander’s ETA and probability of formaldehyde exposure.

Table 7 Assessing the risk of formaldehyde exposure in the process of molding grinding wheel.

Preventive measures for exposure to formaldehyde	Severity	Severity level	Likelihood (%)	Probability level	Risk level
Improper working layout in combination with life expectancy of respiratory protection equipment exceeds its service life.	Significant	4	3.58	1	4
Improper working layout in combination with inappropriate wearing respiratory protective devices to reduce exposure to formaldehyde.	Significant	4	59.82	4	16

Preventive measures for exposure to formaldehyde	Severity	Severity level	Likelihood (%)	Probability level	Risk level
Improper general exhaust ventilation in combination with life expectancy of respiratory protection equipment exceeds its service life.	Significant	4	0.2	1	4
Improper general exhaust ventilation in combination with inappropriate wearing respiratory protective devices to reduce exposure to formaldehyde.	Significant	4	3.43	1	4
Improper general exhaust ventilation, improper working layout in combination with life expectancy of respiratory protection equipment exceeds its service life.	Significant	4	1.26	1	4
Improper general exhaust ventilation, improper working layout in combination with inappropriate wearing respiratory protective devices to reduce exposure to formaldehyde.	Significant	4	21.01	3	12

The risk ranking of formaldehyde exposure due to failure of preventive measures in grinding wheel process can be summarized as follows:

1) Improper working layout in combination with inappropriate wearing respiratory protective devices to reduce exposure to formaldehyde were a high level of risk, preventive measures must be taken to reduce the risks to an acceptable level. The risk mitigation measures included directing the air flow through the operators before reaching the source of formaldehyde, installing a local exhaust ventilation system, a quantitative fit test (QNFT) can be used to fit-test any tight-fitting respirator. It involves using an instrument to measure leakage around the face seal and produces a numerical result called a “fit factor.”

2) Improper general exhaust ventilation, improper working layout in combination with inappropriate wearing respiratory protective devices to reduce exposure to formaldehyde were a moderate risk, preventive measures must be taken to control the risks. The risk control measures consisted of preparing a general ventilation system preventive maintenance plan, place the work position as specified, providing an inspection and assessment plan for the wearing of chemical protective masks, training on the use of chemical protection masks, check the wearing of a mask before starting the work, clearly define the person responsible for the inspection of wearing a mask.

Conclusions

The process of grinding wheel contains serious risks such as inhalation of formaldehyde concentration due to formaldehyde considered a highly hazardous chemical in terms of safety and health. Formaldehyde is classified as a Category 1 carcinogen (a human carcinogen) by the IARC and can cause nasopharyngeal carcinoma and leukemia. To address this risk, the results of the risk assessment must be reliable. Consequently, the paper focused on conducting an AHP by Expert Choice V.11 for determining the relative weight or reliability from ETA structure. The probability of an exposure of formaldehyde event can be calculated by the RAM Commander’s ETA software. As a result of the findings, company authorities (chief executive officer, plant manager, supervisor, occupational safety and health officer, etc.) must set up a risk management plan or standard operating procedures. The procedures should include potential failures of measures to prevent exposure to formaldehyde and actions to be taken to prevent exposure to formaldehyde.

In conclusion, the paper will help researchers and occupational safety and health professionals for minimizing potential risks during work in the process of grinding wheel. The further studies may be extended with Fuzzy Analytic Hierarchy Process (FAHP) approach to handle uncertainty in a better way.

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