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Modeling contamination conditions in small-scale industrial areas to estimate health savings benefits associated with remediation

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Abstract

Mercury and dioxin pollution associated with the China Petrochemical Development Corporation's An-shun plant is one of the most severe soil contamination incidents in Taiwan's history. Residents living nearby were exposed to heavy metals and dioxins that led to significant impacts on human health and safety. While many studies related to contamination in large-scale industrial areas have been conducted to evaluate the effects of occupational contaminant exposure, studies related to people who live near small-scale industry areas are less common. In this study, we use the system dynamics modeling to build a media flow pattern for mercury and dioxin in the vicinity of the An-shun plant, simulate the concentrations of the pollutants before and after remediation, and compare the simulated values with the measurements of actual conditions after remediation to evaluate the feasibility and accuracy of the model. This study also estimated the concentration of mercury and dioxin in each food medium to simulate the daily exposure of the human body to these contaminants. Finally, the reduction in mercury and dioxin levels in the study area was used to estimate the total health benefits to the local population. The objective of this

study was to evaluate the application of this methodology to small-scale industrial areas as well as improve the decision-making process before, during, and after remediation of contaminated sites. The results of this study revealed the health benefits to residents living in the Annan District after remediation was completed at the An-shun plant were significant.

1. Introduction

There has been a growing interest in the relationship between mercury and dioxin contamination and potential health effects of occupational exposure in industrial areas (Li et al., 2014; Chen et al., 2015; Asante-Duah, 2017). Accumulation of these toxic pollutants in soils will certainly result in an increase in direct human exposure via inhalation, dermal contact, or intake of soil, as well as indirect exposure via dietary intake of food and drinking water (Rodrigues and Römkens, 2018). It is therefore crucial to develop tools that accurately assess potential risks of human exposure to these pollutants and to determine meaningful threshold exposure concentrations for mercury and dioxin to protect human health and safety.

Human exposure to heavy metals primarily occurs through three major routes, including inhalation, oral ingestion, and the dermal exposure (Asaduzzaman et al., 2017; Li et al., 2017; Rodrigues and Römkens, 2018). Exposure to small amounts of mercury through one or more of these routes can cause serious health problems in humans (WHO, 2013). As a result, many mercury exposure assessments have been conducted in numerous countries in recent decades (Passos et al., 2008; Cordy et al., 2013; Jeevanaraj et al., 2018; Kim et al., 2018), and many organizations have published acceptable mercury exposure limits and levels that are considered to be hazardous or pose a risk to human health (WHO, 2000, 2003).

The primary source of mercury pollution is in the form of vapor, as it is often discharged into the atmosphere by industrial processes and subsequently deposited in surrounding soils and aquatic ecosystems (Cesar et al., 2011; Nakazawa et al., 2016). In addition, soil leaching and erosion can introduce mercury to aquatic systems (Cesar et al., 2011), where ingestion is the primary mercury exposure pathway via the consumption of marine organisms in which organic forms of mercury like methylmercury (MeHg) bioaccumulate at high concentrations in their tissues (Horvat et al., 2003; Nakazawa et al., 2016), and Bruggeman (1982) defined biomagnification as an increase in the levels of contaminants due

to food ingestion. In this respect, Boudou et al. (2005) indicated that dietary fish is the primary source of mercury intake for many populations. While exposure to mercury vapor can be expected, exposure to MeHg+ from fish consumption has become an important concern in urban locales or areas affected by mercury contamination (Scheuhammer et al., 2007; Correia et al., 2014; Fuentes-Gandara et al., 2018).

In addition to mercury, exposure to dioxins also affects human health and may occur through background (environmental) exposure as well as accidental and occupational exposure (WHO, 1998). Over 90% of background exposure is estimated to occur through diet, with food originating from animals being the predominant source (Fries, 1995; Eduljee and Gair, 1996; WHO, 1998). The complete exposure pathway includes the deposition of airborne dioxins onto plant and soil surfaces where it is subsequently ingested by animals in the human food chain (Fries, 1995). More than 95% of blood dioxin exposure is associated with the consumption of food, particularly fish, meat, and dairy products that contain dioxins (WHO, 1998; Science Communication Unit, 2013). Dioxins are highly toxic and can cause reproductive and developmental problems, damage the immune system, interfere with hormones, and can also cause cancer. As described the literature referenced above, human exposure to mercury and dioxins are primarily associated with their presence in the soil (e.g., following atmospheric deposition or accidental spills) and the ingestion of fish where the contaminants bioaccumulate.

In recent years, the issue of environmental quality and its effect on human health and well-being have gained importance in academic and scientific research. Contaminants associated with particular industrial sites often have negative effects on health of individuals who live in nearby residential areas (Bhopal et al., 1988; Phillimore et al., 2000; Yang et al., 2002; Burningham and Thrush, 2004; López-Navarro et al., 2013). Human exposure to contamination from industrial sources is an aspect of great interest from an epidemiologic standpoint (García-Pérez et al., 2012). While there is extensive research related to contamination issues in large-scale industry areas and occupational exposure in these areas (García-Pérez et al., 2012; López-Navarro et al., 2013), the impact of contamination in small-scale industrial areas on the health of people who live nearby is less understood, particularly in areas near specific petrochemical plants.

Petrochemical plants have often been constructed close to cities, and residents who live in neighborhoods close to these plants are considered to be at a high risk to health hazards associated with these plants. These petrochemical complexes are also frequently located in or near seaports, which constitute a direct contaminant pathway to the environment through the discharge of chemical substances into the water, air, or soil (Yang et al., 2002; Gariazzo et al., 2005; Kaisarevic et al.,

2007; Gatto et al., 2009; López-Navarro et al., 2013). Most previous occupational exposure studies have been primarily focused on the analysis of risk perception and effects on the health of workers in those industry (Flin et al., 1996; Paustenbach et al., 1997; Kao et al., 2008; López-Navarro et al., 2013). However, the potential exposure of mercury and dioxin contamination may also be substantial for inhabitants living in nearby residential zones during the production and refining of crude oil and its derivatives, seriously affecting their health and well-being (Gamero et al., 2011; Signorino, 2012).

Since human exposure to mercury and dioxin contamination in and near small-scale industrial areas is under represented in the body of research, it represents an important focus that warrants attention. Hence, to fill this gap in knowledge, the purpose of the study was to explore the health conditions before and after the remediation of contamination in a small-scale industrial area around the China Petrochemical Development Corporation's An-shun plant, which is considered to be one of the most serious soil pollution incident in Taiwan's history. This has been undertaken to provide an alternative solution accurately modeling contamination and related effects on human health in small-scale industrial areas. Additionally, it may serve as a basis for the decision-making process before, during, and after remediation is conducted. The simplicity of the methodology should enable the researchers and decision makers to identify important details in these small-scale industrial areas without the usual problem of having to use complex system modeling and health risk assessment.

2. Materials and methods

2.1. Defining the dynamic system to be modeled

A well-known case of industrial pollution is the Sinopec An-shun plant pollution case, which is regarded as one of the most severe soil contamination incidents in Taiwan's history. The China Petrochemical Development Corporation's An-shun plant mainly produced caustic soda, hydrochloric acid, liquid chlorine, bleaching powder, bromine, and pentachlorophenol, and it was known as one of the largest pentachlorophenol production facilities in East Asia. Throughout the life of the plant, toxic contaminants produced from the various processes, especially mercury and dioxin flowed continuously into the environment surrounding An-shun plant and severely impacted the surrounding ecology (Zhaoru, 2015). In addition, the chlor-alkali process is an industrial manufacturing for the electrolysis of sodium chloride via the sludge and wastewater to the surrounding sediment and occurred the mercury pollution as well as making sodium pentachlorophenol produces dioxin to long-term exposure to rain and occurred the dioxin pollution.

In 2004, the Environmental Protection Administration in Taiwan designated the plant and the surrounding area as a contaminated site requiring remediation to allow the health of fishes in the ponds to recover. The court ordered the An-shun plant's owner to remediate soil contamination at the site. The China Petrochemical Development Corporation began implementation of the remediation plan used the sediment wet excavation technology to carry out the sea pool bottom mold remediation project in 2009.

After five years of the first phase of remediation (May 2009 to May 2014), portions of the remediation project were not able to achieve the expected targets. Although the residual contamination will be addressed in the second phase of remediation (May 2014 to May 2024), the contaminants that persist are currently able to enter in the food chain through the environment, consequently endangering human health. Hence, the China Petrochemical Development Corporation's An-shun plant was specifically selected for this study to address the issues already outlined and begin to fill the gaps in the previous research (Flin et al., 1996; Paustenbach et al., 1997; Kao et al., 2008; López-Navarro et al., 2013).

2.2. Modeling instruments and procedures

This study used dynamic system modeling to build each media flow pattern of mercury and dioxin flow around the An-shun plant, to simulate the mercury and dioxin concentration before and after contamination remediation, and compare to the simulated results to actual measurements to actual measurements published by the Environmental Protection Administration in Taiwan to prove the feasibility in this modeling. The study also simulated the concentration of mercury and dioxin in each food medium and estimated the daily contaminant exposure. Finally, the reduction of mercury and dioxin was evaluated in terms of the effect on health in the local population. The steps used to establish the mercury and dioxin flow patterns around the An-shun plant were as follows:

- Step1: Each medium was assumed to be in static mass balance in 2003, and the input of each environmental media reservoir was equal to its output. Using the "SOLVER" function in Microsoft Excel, the coefficient of flux of the environmental medium to reach the static balance between each environment medium was calculated.

- Step2: Each environmental stockpile and each media circulation estimated value were entered into the mode simulation of this study structure. The simulation period was set at 30 years (2004−2033), with the first stage of remediation set at 2009−2013 and the end of the period set 20 years (2013−2033) after the end of the first stage.

- Step3: Using actual contaminant measurements from the site and the model simulation values, the feasibility of the simulation was evaluated for its ability to obtain the environmental medium dynamic mercury concentration and human mercury exposure concentration changes. This study established a dynamic system model for mercury and dioxin flow in and around the China Petrochemical Development Corporation's An-shun plant. Schematic models of mercury and dioxin flow are depicted in Figs. 1 and 2, respectively.

2.3. Quantifying human health effects

Quantifying the health effects associated with mercury and dioxin exposure in the An-shun plant area was accomplished with an air resource co-benefits (ARCoB) model (Chen et al., 2013, 2017). The ARCoB model, which was developed on the basis of a simple box model, local statistical data and air pollution control regulations can be applied to generate theoretical constructs for reducing APs and GHG emissions as well as health effect of toxics, and this methodology have been applied in several recent studies (Shih et al., 2016; Chen et al., 2017; Tseng et al., 2017). Regarding the MeHg and Hg concentrations in hair, as well as dioxin and dioxin concentration in blood, the following relationships are applicable.
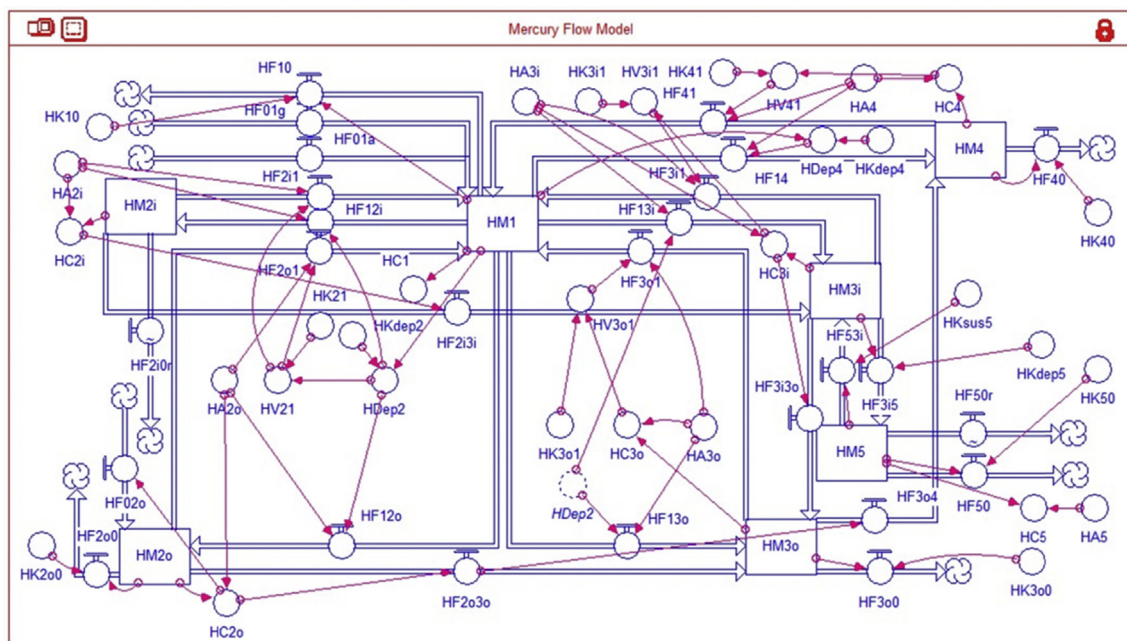

Fig. 1. Dynamics system model of mercury flow around An-shun plant. The mercury flows of the different media include air, outside plant-land, inside the plant-land, outside plant-freshwater, inside the plant-freshwater, ocean mass and sediment around A-shun plant were established by STELLA. Each medium has the relationship and influence with each other.
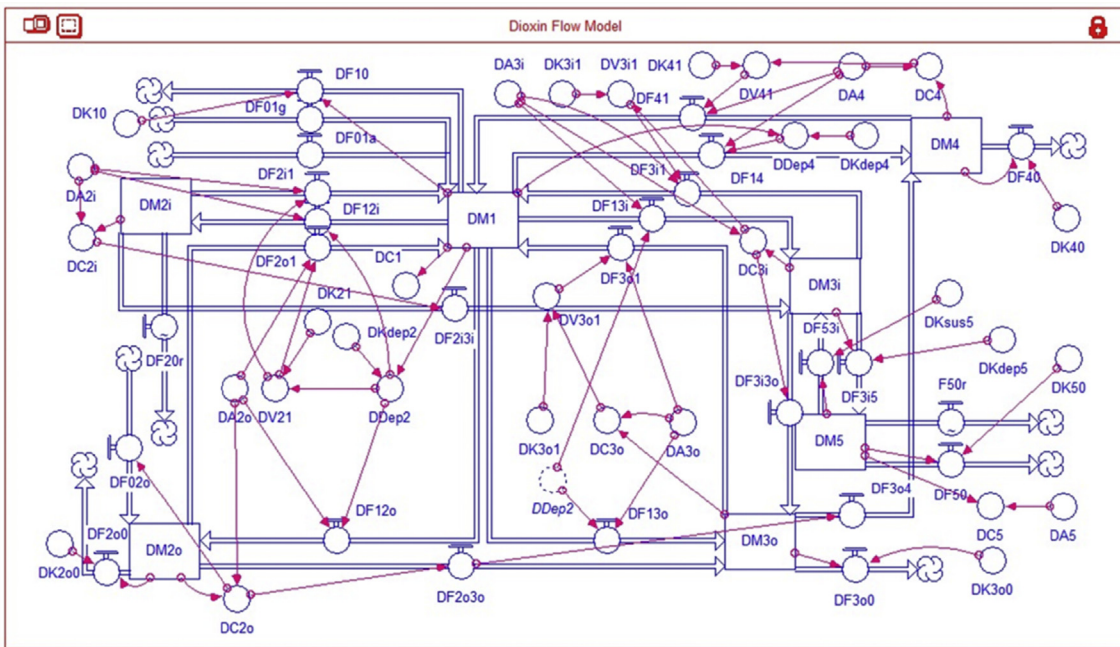
Fig. 2. Dynamic system model of dioxin flow around An-shun plant. The dioxin flaws of the different media include air, outside plant-land, inside the plant-land, outside plant-freshwater, inside the plant-freshwater, ocean mass and sediment were established by STELLA. Each medium has the relationship and influence with each other.

The long-term mercury exposure in humans can be assessed by analyzing mercury concentrations in the hair, and hair sampling is more convenient than sampling of human tissue. This study refers to the results from Cohen et al. (2005) that indicated a daily intake of methylmercury of 1 µg/d results in an increase in the total mercury concentration in hair of 0.17 µg/g. The concentration of MeHg in hair is estimated by Eq. (1),

$$C_{hair} = E_{MeHg} \times 0.17 \tag{1}$$

Quantifying the relationship between contaminant concentration and mortality rate can be accomplished using the ARCoB model (Chen et al., 2013, 2017), where the relative risk (RR) is used to calculate exposure-response regression coefficients and concentration-response functions (CRFs), which are expressed as the percentage change in number of cases per person per change in concentration (µg/m^3). The CRFs are also called "exponential slope factors," and are derived using Eq. (2),

$$CRF_s = \beta = (InRR_{ref}) \div C_{ref} \tag{2}$$

where RR_{ref} is the relative risk of the reference contaminant, and C_{ref} is exposure concentration of the reference contaminant.

On the evaluation of averted morbidity for the whole population, this study refer to the results from Chen et al. (2013, 2017), considers only the medical treatment costs, i.e. the physical impacts, due to that there is no willingness-to-pay for Taiwanese. The approved medical benefit payments to contracted health care institutions are adopted as lower-bound estimates of national medical expenditures.

In this study, for every 1 ppm increase in mercury concentrations, the male all-cause mortality rate increased by 5.0% (95% CI, 1%−9%, p = 0.018), resulting in a relative risk (RR) of 1.05. The dose-response functions of the concentration and all-cause mortality were 4.88%. In addition, regarding to dioxin and dioxin concentration in

Table 1. Comparing measured values and simulated values for mercury concentration.

	Unit	Measured values (from previous research)	Simulated values (in the year of 2033)
Air Mass	ng/Nm^3	3.97	2.41
Outside plant-Land Mass	mg/kg	0.13	0.142
Inside plant-Land Mass	mg/kg	2.89	23.5
Outside plant-Freshwater Mass	ng/L	ND (<92)	38.7
Inside plant-Freshwater Mass	ng/L	1000	1798
Ocean Mass	ng/L	0.4	2.20
Sediment Mass	mg/kg	<1	3.456

Table 2. Comparing measured values and simulated values for dioxin concentration.

	Unit	Measured values (from previous research)	Simulated values (in the year of 2033)
Air Mass	ng/Nm^3	0.04	0.0478
Outside plant-Land Mass	mg/kg	1.067	1.742
Inside plant-Land Mass	mg/kg	932.3	1089
Outside plant-Freshwater Mass	ng/L	0.31	0.262
Inside plant-Freshwater Mass	ng/L	58.69	75.16
Ocean Mass	ng/L	0.01	0.0189
Sediment Mass	mg/kg	<150	0.0478

blood, if the average lifetime exposure is 1 pg/kg-day, the concentration of dioxin in the blood is between 7-8 pg TEQ/g lipid. This study used this to estimate and assume that the concentration of dioxin in the blood changes after exposure to dioxin in various environmental media.

3. Results and discussions

This study established a dynamic system model of mercury and dioxin flow using STELLA (Figs. 1 and 2). In addition, clarified the reduction of mercury and dioxin concentrations in relation to human exposure and the effect on human health using an ARCoB model (Chen et al. 2013, 2017). The following results were ascertained from the modeling efforts.

- This study utilized concentrations of contaminants in various media reported in previous research for comparison with the simulated results from STELLA model. The simulation of mercury and dioxin flaw in this study is very close to the actual measured values reported in previous research (See Tables 1 and 2). The paper on Hope (2008) simulated the Polychlorinated Biphenyls flow distribution with the system dynamics software STELLA. The error between the measured value and the simulated value was within 10 times, which is equivalent to the present study. The estimated result of this study is reasonable.

- With respect to MeHg exposure, the average daily exposure to MeHg in adults has declined each year since the beginning of 2003. WHO (1998) recommends a provisional tolerable weekly intake (PTWI) for MeH should be lower than 1.6 µg/kg. This study estimated MeHg exposure from consuming freshwater fish caught outside the plant boundary area at 1.3 µg/kg, which is below the PTWI, but estimated MeHg exposure from consuming fish caught inside the plant boundary area at 5.24 µg/kg, which is 3 times the acceptable limit. Hence, with respect to MeHg, the consumption of fish caught within the boundary area

of the China Petrochemical Development Corporation An-shun plant is not recommended.

- With respect to dioxin exposure, the daily lifetime average daily exposure to dioxin has been declining each year since the beginning of 2003. WHO (1998) recommends an intake between 1-4 pg I-TEQ/kg-d per person. This study estimated dioxin exposure from consuming fish caught outside the plant boundary at 3.064 pg I-TEQ/kg-d per person in 2003, which is below the recommended intake limit, but estimated dioxin exposure from consuming fish caught inside the plant boundary area was 21.068 pg I-TEQ/kg-d in 2033, which is 7 times greater than the recommended limit. Hence, with respect to dioxin, the consumption of fish caught within the boundary area of the China Petrochemical Development Corporation An-shun plant is not recommended.

- This study estimated the dioxin concentration in the blood for residents who consumed the outside plant freshwater fish and inside plant freshwater fish was 22.98 pg TEQ/g lipid and 423.2 pg TEQ/g lipid, respectively. The 22.98 pg TEQ/g lipid result was similar to the average dioxin concentration of 20 pg TEQ/g lipid that was reported in the Taioxing An-shun plant's dioxin pollution report (Huang, 2002). Therefore, the estimated concentration was similar to the measured concentration, which confirms the applicability and feasibility of the estimation method used in this study.

- With respect to human methylmercury exposure, through methylmercury concentrations in the fish and daily fish, which is consumed on a daily basis, daily methylmercury exposure showed a year-over-year decline similar to the trend in fresh water concentrations. After the exposure to methylmercury was reduced, the weekly exposure of methylmercury to freshwater fish outside the food plant site was 1.3 μg/kg, which did not exceed the weekly methylmercury recommended intake of 1.6 μg/kg. The weekly exposure of methylmercury was 5.24 μg/kg, which was more than three times higher than the standard and was more than four times higher than the weekly exposure of freshwater fish outside the food plant site.

- The study used the ARCoB model (Chen et al., 2013, 2017) to quantify the health benefit associated with reducing mercury and dioxin exposure for residents that live near the An-shun plant area in the Annan District in Tainan City. Residents who consumed freshwater fish caught outside the plant boundary area realized a health savings benefit between 2003 and 2013 of US$25 million and a health savings benefit between 2003 and 2033 of US$41 million. In addition, residents who consumed freshwater fish caught outside the plant boundary area realized a health savings benefit between 2003 and 2013 of US$160 million and a health savings benefit between 2003 and 2033 of US$216 million.

4. Conclusions

This study examines the health conditions before and after the remediation of mercury and dioxin contamination in a small-scale industrial area, but its applicability to large-scale industrial areas is also apparent. Comparing the simulated mercury and dioxin concentrations before and after remediation with the actual values published by the Environmental Protection Administration in Taiwan indicated a difference that was within 10 times; thus, Hope's (2008) research results are generally equivalent to the results of this study, indicating that the simulation model of this study is feasible. The reason for the observed differences between the simulation and actual results may be owing to the lack of some locally-related parameters, such as water concentrations at the plant site and total concentrations of mercury in the air in the simulation process.

Exposure to dioxin in humans, through the HHRAP Health Risk Assessment Model (2005) and the daily intake of foods, the lifetime daily average of dioxin exposure has been declining annually, and the trends are similar to those of freshwater concentrations. After the exposure to dioxin was reduced, the initial year of freshwater fish exposure outside the food plant site was 3.064 pg I-TEQ/kg-d, which did not exceed the daily permissible intake per person recommended by WHO of 1−4 pg I-TEQ/kg-d. The exposure of freshwater fish in food premises was 21.068 pg I-TEQ/kg-d after 10 years, which was more than 7 times higher than the standard and was more than 10 times higher than the exposure of freshwater fish to the edible plants.

Residents who consumed freshwater fish caught outside the plant boundary area from the beginning of 2003 could expect a health-related savings of US$25 million per year after 10 years and US$41 million per year after 30 years. Residents who consumed freshwater fish caught inside the plant boundary area from the beginning of 2003 could expect a savings of US$160 million per year after 10 years and US$216 million per year after 30 years.

The findings of this study led to a feasible modeling and assessment method for contaminated small-scale industrial areas, especially those related to the petrochemical industry. However, much more also needs to be known about potential exposure to contaminants, such as feelings of uncertainty, psychosocial anxiety, and distress which have a wide range of effects on health and well-being. Health risks resulting from the cumulative effects of different contaminant sources constitute an essential component of risk management decision-making aimed at protecting residents (Sexton and Linder, 2010; Lewis et al., 2011; Sexton, 2012), and people exposed to potential chemical hazards are also interested in policies the government agencies use in their management of risk to ensure a safe environment (Spiegel and Maystre, 2012).

This study provides a foundation for future research in this area. Although it is unclear whether the approach described and utilized in this study is applicable to other

small-scale or large-scale industry areas, such analyses would be of particular interest and value in future research.

Declarations

Author contribution statement

Chao-Heng Tseng, Ling-Ling Chen, Po-Chun Yeh: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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