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ASSESSMENT OF ENVIRONMENTAL FACTORS IN INDUSTRY

POSUDZOVANIE ENVIRONMENTÁLNYCH FAKTOROV V PRIEMYSLE

Abstract

With the recent thrust in environmentally conscious manufacturing, there is a need for evaluating the environmental impact of waste streams at the process level. These waste streams occur in different states, have different transport mechanisms and different impacts on the health and safety of operators. This paper presents a hazard scoring system that evaluates the potential hazard to workers exposed to the waste streams in machining processes. The analysis is restricted to a control volume around the process and does not consider far-field ecological effects. The system is based on a number of factors. It incorporates uncertainty in the impact scoring.

Abstrakt

Pri súčasnom tlaku na environmentálne vhodnú výrobu existuje potreba posudzovania environmentálnych dopadov toku odpadov na úrovni obrábania. Tieto toky odpadov sa vyskytujú v rozdielnych skupenstvách, majú rôzne transportné mechanizmy a rôzne dopady na zdravie a bezpečnosť pracovníkov. Tento článok prezentuje hodnotiaci systém nebezpečnosti pre zdravie, ktorý posudzuje potenciálnu nebezpečnosť pre pracovníkov, ktorí sú vystavení toku odpadov pri strojárskych procesoch. Analýza je obmedzená na kontrolný objem na technologickom pracovisku a neuvažuje s ďalekosiahlymi environmentálnymi účinkami. Systém je založený na množstve faktorov. Zahŕňa neistotu v hodnotení dopadu.

1 INTRODUCTION

Traditionally, design and process planning decisions have focused on improving the functionality of the product from a design point of view and increasing the production rate and quality from a manufacturing point of view. The characteristics of the process responsible for this impact (energy consumption and waste streams) are driven by the product design, setup and operating parameters. In a concurrent engineering framework, these environmental factors must be considered along with traditional manufacturing factors of production rate and quality in product and process planning decisions.

Two significant issues exist when evaluating and minimizing the environmental impact of manufacturing processes: increase in complexity of the process planning problem and impact analysis of individual waste streams.

In a generalized model of pollution is developed in which pollutants enter the environment from a source and reach a receptor, causing an undesired effect (Figure 1).

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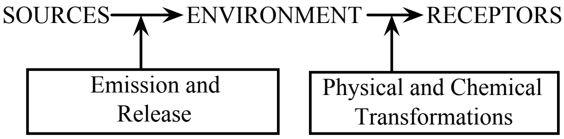

Fig. 1 Generalized Pollution Model

The impact analysis involves several dissimilar waste streams, including the chip volume, tool workpiece particulates, worn tools, cutting fluid mist, cutting fluid contaminated on chips, evaporated cutting fluid, and machine tool lubricant. It is apparent that these waste streams occur in different physical states (solid, liquid, vapor), resulting in different impacts on the environment. This paper presents a quantitative methodology by which the waste mass flow may be characterized by its potential for human health hazard. This hazard characterization is then incorporated into a general decision support tool that can be used to drive a range of decisions including selection of the machining process, workpiece and tool material, cutting fluid, setup and operating parameters.

2 STRUCTURE OF AN ENVIRONMENTAL BASED DECISION MODEL

The decision model is driven by an analytical description of the machining process that identifies interactions among mechanics, tool wear, fluid flow and chip formation. This paper develops a more comprehensive impact scoring procedure (Figure 2) to analyze the waste streams of the machining process.

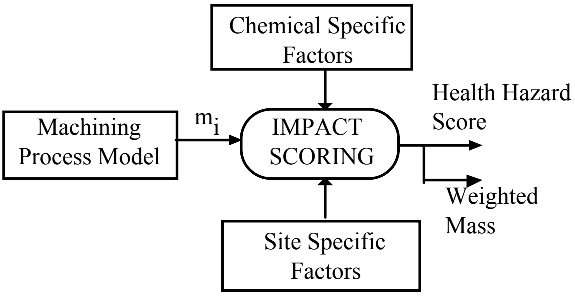

Fig. 2 Decision Model for waste stream evaluation

Different machining processes generate varying types of wastes. In turning, the solid waste stream appears in the form of chips and worn tools, while the liquid waste stream appears in the form of coolant dissipated in various forms. The physical properties of the tool and workpiece materials also have a significant impact on the type and quantity of waste that is generated. Coolants are a major source of environmental concern during usage and disposal.

The impact scoring system is based on evaluating the different waste streams for their potential hazard based on various effects: oral toxicity, inhalation toxicity, dermal (skin) irritation, eye irritation, carcinogenicity, flammability, and chemical reactivity. A formalized weighting scheme utilizing the Analytic Hierarchy Process (AHP) [6] is developed to prioritize these effects based on site specific human behavior and fate and transport mechanisms in order to collapse the multidimensional scores into a scalar index. This score is then used to weight the raw mass flow of the waste stream to signify its environmental impact.

3 DATA REQUIREMENTS

There are seven effects which can be grouped into three broad categories according to the type to data they require. The first is toxicological effects (oral and inhalation toxicity, dermal and eye irritations). The next is cancer effects, expressed as a risk (carcinogenicity), and the last is physical effects (flammability and reactivity). The quantification of these effects is limited to a control volume around the process. The present analysis does not extend to far-field population or chronic effects such as soil contamination, ozone depletion, or atmospheric dispersal of contaminants.

3.1 Toxicological Effects

In characterizing the hazard of a chemical substance such as a cutting fluid, two parameters of interest are exposure and effect. Exposure concerns the pathway by which a substance enters the person. The toxicological impact of a substance is characterized by a dose-response curve (Figure 3). This curve is a cumulative distribution function giving the proportion of a certain population of exposed organisms that responds with a specified effect as a function of the administered dosage (normalized by body weight).

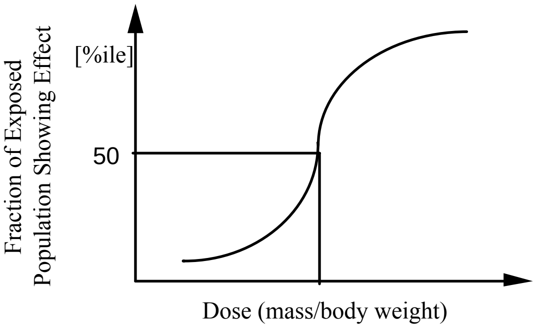

Fig. 3 Dose-Response Curve

The curve shows that across individual organisms, there is a variation in the dose required to induce a particular effect. It should be noted that each curve represents the dose-response behavior of a certain species to a given substance for a specified effect.

Cancer Effects

Carcinogenesis is a multistage process in which carcinogenic chemicals act by initiating certain genetic changes in a cell, ultimately causing a tumor to form.

Physical Effects

For the purposes of this scoring system, the two physical hazards of interest are flammability and chemical reactivity.

4 HEALTH HAZARD SCORE FORMULATION

There are several key features of the scoring system:

- ☐ Data regarding different substances are drawn from the manufacturer's material safety data sheets (MSDS), the ACGIH-TLV handbook [1] and RTECS files [5].
- ☐ Each substance is assigned a sub score for each effect of interest. These are: oral toxicity (O), inhalation toxicity (I), dermal irritation (D), danger to eyes (E), carcinogenicity (C), flammability (F), and chemical reactivity (R).
- ☐ Sub scores of multiple component waste streams are weighted by mass fraction.
- ☐ For the toxicological effects (O, I, D, E), the sub score is the product of a dose and an effect ranking, with an overall score of 0 to 9. The effect ranking ranges from 0 (no observed effect) to 3 (lethal or maximum effect), and the dose ranking ranges from 1 (large dose) to 3 (small dose). Thus a substance that has a maximal effect (effect ranking 3) with a small dose (dose ranking 3) gets a maximum toxicity sub score of 9: only a small amount is required for the worst effect.

- Where no data exist for an effect, the nominal score is varied from the worst case (assuming the substance is maximally hazardous in this effect) to the best case (assuming the substance is minimally hazardous in this effect). This is used for uncertainty analysis.
- Using the AHP, the multiple sub scores are collapsed into a final, composite, single **Health Hazard Score** (HHS) that characterizes the human health hazard potential associated with a waste stream. A higher HHS denotes a more hazardous substance.
- The HHS serves only as a comparative scale among dissimilar waste streams.

Tab. 1 ORAL TOXICITY (O)

Effect		Dose (LD_{50})	
3	lethal	3	< 50 mg/kg
2	moderately serious	2	50 - 500 mg/kg
1	mild effect (nausea, unpleasant)	1	>500 mg/kg
0	no observed effect		

O = Effect □ Dose, □[0,..,9].

Tab. 2 INHALATION TOXICITY (I)

Effect		Dose (TWA-TLV)	
3	lethal	3	< 50 mg/m^3
2	moderately serious	2	50 - 500 mg/m^3
1	mild effect (nausea, unpleasant)	1	>500 mg/m^3
0	no observed effect		

I = Effect □ Dose, □[0,..,9].

Tab. 3 EYE IRRITATION (E) (RABBIT) [2]

Effect		Dose	
3	lethal	3	< 50 mg
2	moderately serious	2	50 - 500 mg
1	mild effect (nausea, unpleasant)	1	>500 mg
0	no observed effect		

E = Effect □ Dose, □[0,..,9].

Tab. 4 DERMAL IRRITATION (D)

(PATCH TEST RABBIT) [2]

Effect		Dose (TWA-TLV)	
3	severe	3	< 200 mg
2	serious	2	200 to 500 mg
1	mild	1	>500 mg
0	no observed effect		

D = Effect □ Dose, □[0,..,9].

Tab. 5 CARCINOGENICITY (C) [2]

Score	Evidence
8-9	Evidence of oncogenicity from epidemiological studies and/or positive results in two or more mammalian species.
6-7	Evidence of oncogenicity in one or both sexes of a single mammalian species, with or without limited epidemiological data.
4-5	Suggestive evidence (not statistically significant, or confounded by extraneous variables) of oncogenic potential from epidemiological studies, mammalian bioassays (incl. preneoplastic change in vivo), cell transformation in vitro, or promoter/cocarcinogenic activity.
3	Evidence of genotoxic potential.
1-2	Limited evidence of lack of oncogenic potential from epidemiological and/or in vivo/in vitro laboratory data.
0	No evidence of oncogenic potential from well-conducted and well-designed mammalian studies in two or more animal species.

Tab. 6 REACTIVITY (R)

Score	Reacts with
9	metals, oxidizing agents, acids, bases, moist air, water, etc.
8	metals and moist air
7	metals
6	(moist) air
4-5	oxidizing agents
1-3	acids and/or bases
0	no known substance (inert)

Tab. 7 FLAMMABILITY (F)

(FLASH POINT, UEL/LEL)

flash point (˚F)		UEL–LEL (%)	
3	<100	3	>20
2	>100	2	10-19
1	>500	1	1-10
		0	0 (none)

F = flash point score × UEL–LEL score, $\in [0,..,9]$.

For each waste stream, a hazard profile is formed, represented as a 1×7 hazard row vector $\underline{H}$. Each element of the vector represents the potential hazard of the waste stream of the particular effect (oral toxicity, cancer, flammability, etc.). As mentioned above, for cases where data are not available the score is presented as a range. Thus each component of $\underline{H}$ is in fact a paired couple: the minimum and maximum possible sub score for each effect.

5 SITE SPECIFIC PRIORITIZATION

The seven effects considered here have different degrees of importance at different sites depending on such factors as the hazard protection equipment worn by the machinist, the shielding for the machine tool, ventilation and other mechanisms for handling and disposing of cutting fluids, and waste stream transport behavior. Since these factors are difficult to explicitly evaluate, a subjective prioritization is elicited from the user (such as the plant manager or the health and safety director). The elicited prioritizations are placed into a matrix according to the Analytic Hierarchy Process (AHP) in order to formally treat and cardinalize the various effects (see Fig. 4).

$$\mathbf{X} = \begin{array}{c|ccccccc|} & O & I & E & D & C & R & F \\ O & 1 & 1/5 & 1/10 & 1/30 & 1/2 & 1/20 & 1/20 \\ I & 5 & 1 & 1 & 1/10 & 2 & 1/5 & 1/5 \\ E & 10 & 1 & 1 & 1/6 & 2 & 1/4 & 1/3 \\ D & 30 & 10 & 6 & 1 & 15 & 2 & 3 \\ C & 2 & 1/2 & 1/2 & 1/15 & 1 & 1/5 & 1/8 \\ R & 20 & 5 & 4 & 1/2 & 5 & 1 & 1 \\ F & 20 & 5 & 3 & 1/3 & 8 & 1 & 1 \end{array}$$

Fig. 4 Example of a Prioritization Matrix

Based on this matrix, an 1× 7 fate and transport column vector F can be calculated. First a rank value is determined through the following relationship:

$$R_i=\left(\prod_{j=1}^{k} X_{ij}\right)^{\frac{1}{k}} \qquad (1)$$

where X_{ij} are the elements of the $k \times k$ Prioritization matrix **X**. Here, $k = 7$, the number of effects of interest. The elements of F are then determined by a simple normalization.

$$F_i=\frac{R_i}{\sum_{i=1}^{k} R_i},\ i=1,..,k \qquad (2)$$

For the example shown in Figure 4, F was determined to be F = $[0.01\ \ 0.05\ \ 0.07\ \ 0.43\ \ 0.03\ \ 0.21\ \ 0.20]^T$. The final hazard score HHS (a scalar) is the vector dot product of the hazard profile row vector H and the site-specific fate and transport column vector F, that is,

$$HHS = \underline{H} \bullet \underline{F} \qquad (3)$$

This score is then used to weight the particular waste stream, giving the weighted total mass flow m_W, as

$$m_W=\sum_{i=1}^{n} (1+HHS_i)m_i \qquad (4)$$

where n is the total number of waste streams considered and m_i is the raw mass flow of the i^{th} waste stream.

6 ILLUSTRATIVE EXAMPLE

To illustrate the use of this scoring system, a typical oil-based cutting fluid, whose constituents are listed in Table 8, is examined. The information was obtained from the MSDS of the cutting fluid.

Tab. 8. CUTTING FLUID CONSTITUENTS

Component Name	CAS #	% comp.	wts(w)
1,1,1 trichloroethane	71-55-6	90	0.9
tert-butyl alcohol	75-65-0	2	0.02
1,2-Butylene Oxide	106-88-7	2	0.02
Dimethoxymethane	109-87-5	2	0.02
Petroleum oil, aliphatic	68815-10-1	2	0.02
Vegetable oil, essential	104-55-2	2	0.02

Using data available in the RTECS files, we rank this fluid for each of the end-points of interest in the tables below. Where no data are available, 'nd' is used while ‘err,’ denotes the amount by which the score could vary between minimum and maximum values. The final sub score is D x E x w, the product of the dose, effect and mass composition weight.

Tab. 9. ORAL TOXICITY SCORE

Component name	D	E	D X E	D x E x w	err
1,1,1 trichloroethane	1	3	3	2.7	0
tert-butyl alcohol	1	3	3	0.06	0
1,2-Butylene Oxide	2	3	6	0.12	0
Dimethoxymethane	1	3	3	0.06	0
Petroleum oil, aliphatic	Nd				0.18
Vegetable oil, essential	1	3	3	0.06	0
			Final	3.00	0.18

The final sub score for oral toxicity (weighted by mass proportion) is a minimum of 3.00 and a maximum of 3.18, depending on the currently unavailable data on petroleum oil, aliphatic.

All sub scores, elements of the hazard vector, $\underline{H}$, are summarized in Table 10.

Tab. 10. $\underline{\mathbf{H}}$ VECTOR

Effect	$\underline{H}_{min}$	$\underline{H}_{max}$
Oral toxicity (O)	3.0	3.2
Inhalation toxicity (I)	1.0	1.3
Eye irritation (E)	8.2	8.9
Dermal irritation (D)	5.6	6.2
Carcinogenicity (C)	2.9	2.9
Reactivity (R)	7.6	7.8
Flammability (F)	1.08	1.4

The above table represents a human health effects profile of the cutting fluid under examination. The different ranges in the score attest to the varying levels of data availability. At this point, the final, scalar HHS is derived from this profile using the prioritization of effects supplied by the user. The user defines the extent to which each of the several effects, relative to one another, is likely to be mitigated due to site-specific preventive measures, such as protective gear, material handling practices, equipment modifications and facility design. For example, if all workers were required to wear eye protection but not rubber gloves, skin irritation may then be ranked more heavily than eye irritation. These evaluations are placed into the AHP matrix in order to capture the site-specific circumstances ($\underline{F}$) that may mitigate or accentuate the chemical-specific human health effects ($\underline{H}$). Using Equation (3), the lower and upper-bound HHS can be determined as:

$$HHS_{min} = \underline{H}_{min} \bullet \underline{F} = 4.9$$

$$HHS_{max} = \underline{H}_{max} \bullet \underline{F} = 5.4$$

Suppose a second cutting fluid (Fluid B) has a HHS range of [5.1, 5.9], as compared to the range of [4.9, 5.4] of the above fluid (Fluid A), we have an overlap condition corresponding to Case 2. Using Eq. (7), the confidence level for selecting Fluid A over Fluid B is 70%.

7 DISCUSSION

The scoring system is meant to remain straightforward while adequately treating the complexity of the machining process/worker interaction. There are several sources of complexity. First, for the sake of completeness, many different human health effects (such as skin irritation, respiratory reactions, etc.) must be considered, necessitating a multidimensional measure of effects on persons inside the workplace. Second, waste streams in the machining environment are very complex composites of numerous substances in various physical states. Third, the scoring process is data-intensive, and relies in particular on toxicological data which are often either missing or incomplete.

Typical water based cutting fluids are subject to attack from bacteria and fungi. The growth of such micro organisms has been the predominant cause of fluid failure. To control such microbial growth, biocides are added to cutting fluids. However these biocides have side effects such as dermal irritation. The effect of biocides can be easily incorporated to the scoring system by including them as additional constituents of the cutting fluid.

8 CONCLUSION

A health hazard scoring system has been introduced for the evaluation of manufacturing wastes and applied to the machining process. The system relies on a data intensive scoring process of the various waste stream constituents as to their relative potential hazard to humans. Uncertainty due to incomplete information is formally treated, allowing new data to be incorporated into the framework. The system should provide a viable method for manufacturing decision support which incorporates environmental criteria in process planning.

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