Journal of Hazardous Materials 172 (2009) 423–431

Contents lists available at ScienceDirect

Journal of Hazardous Materials

journal homepage: www.elsevier.com/locate/jhazmat

Combining U.S.-based prioritization tools to improve screening level accountability for environmental impact: The case of the chemical manufacturing industry

Xiaoying Zhou, Julie M. Schoenung*

Department of Chemical Engineering and Materials Science, University of California, Davis, Davis, CA 95616, United States

ARTICLE INFO

Article history:
Received 16 April 2009
Received in revised form 8 July 2009
Accepted 8 July 2009
Available online 15 July 2009

Keywords:
Characterization factor
Chemical hazards
Environmental impact assessment tools
Pollution prevention

ABSTRACT

There are two quantitative indicators that are most widely used to assess the extent of compliance of industrial facilities with environmental regulations: the quantity of hazardous waste generated and the amount of toxics released. These indicators, albeit useful in terms of some environmental monitoring, fail to account for direct or indirect effects on human and environmental health, especially when aggregating total quantity of releases for a facility or industry sector. Thus, there is a need for a more comprehensive approach that can prioritize a particular chemical (or industry sector) on the basis of its relevant environmental performance and impact on human health. Accordingly, the objective of the present study is to formulate an aggregation of tools that can simultaneously capture multiple effects and several environmental impact categories. This approach allows us to compare and combine results generated with the aid of select U.S.-based quantitative impact assessment tools, thereby supplementing compliance-based metrics such as data from the U.S. Toxic Release Inventory. A case study, which presents findings for the U.S. chemical manufacturing industry, is presented to illustrate the aggregation of these tools. Environmental impacts due to both upstream and manufacturing activities are also evaluated for each industry sector. The proposed combinatorial analysis allows for a more robust evaluation for rating and prioritizing the environmental impacts of industrial waste.

1. Introduction

Environmental indicators allow industrial facilities and government regulators to quantitatively assess the environmental performance associated with specific manufacturing practices. To date, the most common environmental indicators used to establish compliance with regulatory requirements for an individual facility and to benchmark various industries have been aggregated quantity of emission or, alternatively, amount of waste generated. This approach is typical of the traditional "command and control" mode of environmental management. For example, the U.S. Environmental Protection Agency (EPA) Toxics Release Inventory (TRI) represents one of the most well known databases for chemical releases into various media, such as air, water and land [1]. Because of its relative simplicity, it is fairly common to use the metrics in the TRI directly as a primary environmental indicator to establish priority while the potential effects on human and environmental health of the chemicals being released are often not directly considered. Clearly, a strategy of source reduction and pollution prevention is best served when the analysis incorporates all potential effects. Ideally, such an approach represents a paradigm shift from a simplistic, one or two factor linear decision making strategy to an analysis that invokes quantitative environmental indicators to properly prioritize the environmental performance of industry and uses this information to optimize pollution prevention concerns, i.e., to target time, effort and limited resources to address chemicals with the greatest environmental footprint.

In light of the above discussion, the objective of this study is to use combinatorial analysis to evaluate and combine several established quantitative environmental and health evaluation schemes for guiding pollution prevention and environmental management activities as applied to the chemical manufacturing industry (NAICS 325 or SIC 28[1]) in the United States. The chemical industry has been recognized as a polluting sector, which is associated with large quantities of hazardous waste and toxic emissions. A total of 19 subcategory industry sectors were investigated in this study. In view of the fact that the chemical manufacturing industry involves diverse activities and numerous products, the analysis is presented in terms

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* Corresponding author.
E-mail address: jmschoenung@ucdavis.edu (J.M. Schoenung).

[1] NAICS, North America Industry Classification System; SIC, Standard Industry Classification.

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doi:10.1016/j.jhazmat.2009.07.032

of a normalized economic unit representing one million dollars of economic activity. The relationship between economic transactions and toxic emissions can be tracked with a publicly accessible software tool, Economic Input–Output Life Cycle Assessment (EIO-LCA). The environmental emissions data sources in EIO-LCA are derived from the U.S. EPA's 1997 TRI and 1997 value of shipments from the 1997 Annual Survey of Manufacturers [2]. It is recognized by the authors of this study that the use of TRI data from EIO-LCA has its shortcomings for two primary reasons. First, the data sources and references used in EIO-LCA are out-dated and not dynamically updated with the annual reported TRI database and Input–Output Commodity Matrix, thus there may be discrepancies between the TRI data used in this study and the current actual manufacturing activities and environmental performance. Second, the TRI database itself has some inherent limitations, such as self-reported data and changes over time in the U.S. EPA's reporting requirements.

The potential inaccuracies created by the use of TRI data do not detract from the principal objective of the current study, which is to propose a new methodology using a select group of existing environmental assessment tools to go beyond the quantitative measure TRI provides. With this goal in mind, we emphasize toxicity-perspective characterization factors in the evaluation schemes utilized in this work, and we implement the evaluation schemes in combination to screen and prioritize chemicals and industrial sectors.

2. Comparison of evaluation schemes

2.1. General

As an alternative to focusing only on the quantity of waste released, there are some prominent U.S.-based quantitative assessment tools that can be implemented to evaluate multiple impact categories, including: Scorecard Risk Scoring System (SRSS), Chemical Process Simulation for Waste Reduction (WAR) Algorithm, Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI), Risk-Screening Environmental Indicators (RSEI), and Indiana Relative Chemical Hazard Score (IRCHS). These assessment tools provide a means to quantify the potential health and environmental impacts associated with the releases from various chemical manufacturing industry sectors. The schemes show differences, however, in their formulation, mathematical assumptions, their scope and applications, and data sources. The general differences are summarized here, with more detail on each method provided below.

Some of the schemes such as WAR and IRCHS use *hazard* or regulatory factors to identify inherent toxicity or carcinogenic potential associated with chemical releases. Some of the schemes such as SRSS and RSEI rely on the mechanisms of *risk* assessment to assess a combined effect of likelihood and hazard (*risk* = probability of release or exposure × *hazard*) [3], which usually comprises a four-step process, i.e., hazard identification, exposure assessment, dose–response assessment and risk characterization [4]. Some of the schemes such as TRACI invoke Life Cycle Impact Assessment (LCIA), and therefore focus on *impact potential*. LCIA usually evaluates additional impact categories beyond the human health and toxicological characteristics considered within risk assessment. The characterization step in LCIA is used to approximate the contributions of chemical releases to environmental impact based on the assumption that the human health effects and environmental impact potential of chemical releases have a linear relationship with the mass flow of chemical release. The slope parameter is defined as the "characterization factor" (i.e., *impact potential* = impact characterization factor × mass of release). The derivation of characterization factors in many cases involves assessment of the fate-exposure mechanism, which is then generalized to a broader spatial and temporal scope. For a more in-depth comparison on the similarities, differences and interactions between hazard assessment, risk assessment and potential impact assessment, the reader is referred to Udo de Haes et al. [5], Pennington et al. [6], and Bare [7]. In selecting a particular evaluation scheme (or combination of schemes), the user should consider the trade-offs between the easier to measure, lower uncertainty metrics of hazard and impact potential and the harder to measure, higher uncertainty, yet more relevant metric of risk [8], as risk assessment demands significant resources and cautious interpretation; also the complexity of risk assessment models leads to greater uncertainty due to the lack of sufficient site-specific data and knowledge.

In the present study, the hazard/risk/impact characterization in the selected evaluation schemes share some similar general methodological bases and relevant mathematical parameters. Thus, the terms "impact" and "characterization factor" are used in a general form for all of the schemes, to facilitate the comparative and combinatorial viewpoint. It should be noted that all of the evaluation schemes were developed by U.S. research institutions and government organizations, adopt U.S.-based data, are publicly available, and have the primary advantage of transparency with full documentation on the underlying algorithms and assumptions, which is why they were selected for this study. Table 1 summarizes the characteristics of these evaluation schemes. Each scheme is described in more detail below.

2.2. Scorecard Risk Scoring System (SRSS)

SRSS was developed by Dr. Hertwich et al. and is based on Toxic Equivalency Potentials (TEPs) [9]. TEPs indicate the relative cancer and non-cancer human health risks associated with a release of one pound of a chemical into air or water, compared to the risk posed by the release of a reference chemical, i.e., benzene for cancer effects and toluene for non-cancer effects. The framework used for the calculation of TEPs involves the CalTOX model (Multimedia Exposure Model for Hazardous Waste Sites). CalTOX utilizes data on a pollutant's physical–chemical properties and the landscape characteristics of the environment and takes into account transport and transformation processes of pollutants to estimate the average daily dose from exposure that is associated with a unit release of a chemical to different environmental media [10]. This estimated dose value is combined with available toxicity data (cancer potency value for carcinogens and reference dose for non-carcinogens) to produce the final value of TEPs, which are expressed as cancer and non-cancer health risk estimated for a unit of a specific chemical released to air or water.

2.3. Chemical Process Simulation for Waste Reduction (WAR) Algorithm

The WAR algorithm is a publicly available methodology developed by U.S. EPA's National Risk Management Research Laboratory to determine the Potential Environmental Impact (PEI) of a chemical process [11]. The PEI is the average recorded environmental effect due to a release from various reference resources. The WAR methodology was specifically developed for application to the design phase for chemical processes and reaction route selection. In the proposed approach, input–output PEI balance is employed into the traditional process design methodology to identify the more environmentally friendly process alternative. But in this case study, we emphasize only the potential environmental effects of specific chemicals as emissions. The WAR algorithm sets up eight environmental impact categories in its evaluation: human toxicity potential

Table 1
Key characteristics of evaluation schemes.

Schemes	Covered impact category	Release media/exposure pathway	Algorithm for impact characterization factor	Relative value? (without normalization)	Covered substances	Developer	Designed application
SRSS	TEPs: cancer and non-cancer chronic health effects	Air and water	Fate and exposure modeling	No	356; includes metals	Environmental Defense	LCA and TRI risk screening
CalTOX based							
WAR	Potential environmental impact: HTPI, HTPE, TTP, ATP, GWP, ODP, PCOP	Inhalation, dermal and ingestion; land and water	Toxicological data and other published data (equivalent factor)	Yes	2117; does not include metals	U.S. EPA Office of Research and Development	Chemical process eco-design
TRACI	Global warming, ozone depletion, acidification, eutrophication, smog formation, ecotoxicity, and human health related effects	Air and water	Midpoint characterization: fate and exposure modeling	No	932; includes metals	U.S. EPA Office of Research and Development	Complete LCA
CalTOX involved for health effects							
RSEI	Cancer and non-cancer chronic health effects; TRI, environmental concentrations, doses, affected population	Inhalation and oral exposure	Toxicological data combined with Weight of Evidence	Yes	149; includes metals	U.S. EPA Office of Pollution Prevention and Toxics	Risk assessment
IRCHS	A single value combined environmental (air, water, land, global) and workplace hazard	Aggregated single value considering media-specific (land, air and water) regulation	Semi-quantitative: score assignment based on regulatory priority or normalized toxicity	Yes	1293; includes metals	Purdue University's Indiana Clean Manufacturing Technology and Safe Materials Institute	Chemical rating system based on hazard
EIO-LCA	Economic activity, air pollutants, greenhouse gases, energy use, TRI, employees	Air, water and land	Amount of releases/emissions	No	609: includes metals	Carnegie Mellon Green Design Institute	I/O LCA and hybrid LCA

Web access for evaluation schemes: SRSS: http://www.scorecard.org/env-releases/def/tep_gen.html; WAR: http://www.epa.gov/nrmrl/std/sab/war/sim_war.htm; TRACI: http://www.epa.gov/nrmrl/std/sab/traci/; RSEI: www.epa.gov/oppt/rsei/; IRCHS: https://engineering.purdue.edu/CMTI/IRCHS/; EIO-LCA: http://www.eiolca.net/.
TEP: Toxic Equivalency Potential; HTPI: human toxicity potential by ingestion; HTPE: human toxicity potential exposure by both dermal and inhalation; TTP: terrestrial toxicity potential; ATP: aquatic toxicity potential; GWP: global warming potential; ODP: ozone depletion potential; PCOP: photochemical oxidation potential; AP: acidification potential; LCA: Life Cycle Assessment; TRI: Toxic Release Inventory; I/O: input–output.

by ingestion; human toxicity potential exposure by both dermal and inhalation; terrestrial toxicity potential; aquatic toxicity potential; global warming potential; ozone depletion potential; photochemical oxidation potential; and acidification potential [12]. Notably, in addition to human health effects, WAR extends the environmental impact category to include ecotoxicity, global warming and ozone depletion effects. However, one limitation of application is that metal and metal compounds are not included in the WAR dataset.

2.4. *Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI)*

TRACI is an environmental assessment tool developed by the U.S. EPA, which was originally designed for life cycle assessment studies [8]. TRACI has a set of characterization factors for specific chemical releases to quantify the major environmental impact effects such as global warming, ozone depletion, acidification, eutrophication, smog formation, ecotoxicity, and human health related effects. For human health effects, TRACI employs the CalTOX derived values proportional to the SRSS model discussed above. In this case study, only chemical releases during the manufacturing stage are taken into account; the other life stages and resource utilization are not employed.

2.5. *Risk-Screening Environmental Indicators (RSEI)*

The U.S. EPA's RSEI model focuses on analyzing chronic human health risk factors only for TRI releases [13]. RSEI's risk-based perspective calculation applies fate, transport, and exposure modeling, but in this case study, we only rely on RSEI's toxicity data for chemicals. The term "toxicity weight" is a chemical-specific value in RSEI and is based upon the single chronic health endpoint for inhalation or oral long term exposure [14]. A chemical's non-cancer effect is based on a Reference Dose (RfD) or Reference Concentration (RfC), combined with appropriate uncertainty factors to account for intraspecies/interspecies variability and extrapolation. Also, modification factors based on the U.S. EPA's professional judgment may apply as a Quality Assurance—Quality Control measure. A chemical's cancer effect is based on the Oral Slope Factor and Inhalation Unit Risk combined with the Weight of Evidence system. An important assumption made in the RSEI model is that a metal and the corresponding metal compounds have the same toxicity weight values.

2.6. *Indiana Relative Chemical Hazard Score (IRCHS)*

The IRCHS is a chemical rating system designed to integrate the environmental impact to the aquatic ecosystem, air quality, potential soil and groundwater contamination, ozone depletion and the workplace hazard to employees into a single dimensionless hazard value, for over one thousand chemicals [15]. The adopted algorithm is transparent but semi-quantitative. For example, within the “global hazard” category, if the chemical is Class I Stratospheric Ozone Depleter (SOD), the value of 50 is assigned; a value of 25 is assigned for Class II SOD. For “land” and “air” categories, the model assigns separate values based on priorities within the regulatory context.

2.7. Economic Input–Output Life Cycle Assessment (EIO-LCA)

EIO-LCA is applied in this case study to establish a link between a “functional unit” of economic activity (i.e., one million dollars of output) with the corresponding toxic release amounts, using the TRI database for the chemical manufacturing industry. The economic based functional unit allows for comparisons among scales of production and across time, providing a method adaptable to all sizes of facilities and sectors. Furthermore, EIO-LCA is built upon the inter-sector transactions as compiled by the Bureau of Economic Analysis of the U.S. Department of Commerce [2]. Thus the evaluation of environmental effects caused by individual industry sectors can be extended to an industry’s supply chain, as is done in our case study. In addition to toxic releases, other environmental data such as on criteria air pollutant emissions, greenhouse gas emissions, and energy usage, are also available in the EIO-LCA model and are utilized in our case study.

3. Comparison of evaluation results at industry level

3.1. Scope of comparison

The chemical manufacturing industry sector is one of the top ten industry groups in terms of toxic releases and hazardous waste generation, based upon a review of the U.S. TRI data and National Biennial Resource Conservation and Recovery Act (RCRA) Hazardous Waste Report, also known as the Biennial Generator Report (BGR). The chemical manufacturing industry (NAICS 325 or SIC 28) is responsible for “the transformation of organic and inorganic raw materials by a chemical process and the formulation of products” [16]. Its products are as varied as industrial gases, plastics, pharmaceuticals, soaps and other cleaning agents, paints, fertilizers, pesticides, cellulosic fibers, adhesives, and explosives as well as acids, alkalis, solvents, reagents, etc. For a clear definition of the boundaries of the chemical manufacturing industry sector, we can apply either SIC codes or NAICS codes (although the use of SIC codes is gradually disappearing, it is still currently employed within the regulatory community and industry). Fig. 1 shows a transformation bridge between these two applicable classification systems of the industrial sectors assessed in this case study.

Due to varied production volumes across time, location and industry sectors, we select an economic activity of one million dollars as the “functional unit” for the purpose of comparison. Interaction and integration of economic activities and environmental impacts can be realized with the EIO-LCA model. Thus, for a specific industry sector, the EIO-LCA model is employed to obtain the value of toxic releases, air pollutants, energy usage and greenhouse gas emissions directly or indirectly (from upstream supply chain activities) triggered by one million dollars of output associated with the selected industry sector. Focusing on toxic releases, chemical-specific impact scores to human health and the environment are derived with the five U.S.-based evaluation schemes discussed in the previous section and are then aggregated to provide a total value for the potential environmental impact caused by each selected industry sector within the United States.

3.2. Priority chemicals

To provide a comparative rating of both the chemical manufacturing industry sectors and of the chemicals released by these sectors, on the basis of potential environmental impact, as derived by combining the select evaluation schemes, we propose the following approach. First, we evaluate the chemicals themselves. To accomplish this we extract TRI data on the chemicals directly discharged by the 19 pre-selected six-digit NAICS chemical manufacturing industry sectors. By applying a cut-off value equal to 1% of total releases by each sector, the list of chemicals released is reduced to a manageable number (72) for further analysis. Thus we derive an $n \times i$ matrix S composed of the release amount S_{ni} of i (=72) chemicals per million dollar output from n (=19) industry sectors. From the perspective of impact potential and employing a simplistic linear assumption (impact potential H = impact characterization factor $T \times$ mass of release S), we derive impact potential values for each sector from each of the five evaluation schemes. It

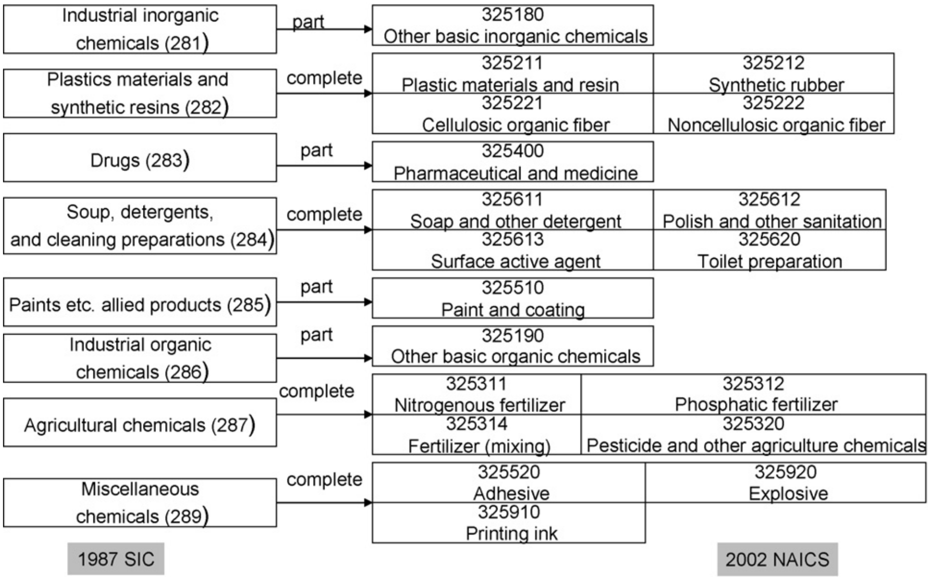

Fig. 1. Transformation of selected chemical manufacturing industry sectors between 1987 SIC and 2002 NAICS classification systems.

Table 2
Chemical prioritization through SRSS evaluation scheme.

i	$S_{i,e}$ (summed by industry sector n)			$T_{i,m,e}$		H_i <H_i'> (SRSS_C)	$T_{i,m,e}$		H_i <H_i'> (SRSS_NC)
Chemical	TRI (air, kg)	TRI (water, kg)	TRI (land, kg)	SRSS_C (air, unit/kg)	SRSS_C (water, unit/kg)	SRSS_C (total, unit)	SRSS_NC (air, unit/kg)	SRSS_NC (water, unit/kg)	SRSS_NC (total, unit)
Ammonia	8,303.57	143.80	17.07	0	0	0 <0>	3.80	0.01	2.13 <31,555.01>
Carbon disulfide	11,708.33	0.72	1.03	0	0	0 <0>	1.2	0.8	0.94 <14,051.29>
Lead compounds	2.08	1.02	1498.71	28	2	1.29 <60.35>	580,000	42,000	83.75 <1,250,674.92>

TRI: Toxic Release Inventory; SRSS_C: Scorecard Risk Scoring System Cancer Effect; SRSS_NC: Scorecard Risk Scoring System Non-cancer Effect; i, chemicals; S_i, absolute amount of release for chemical i; $T_{i,m,e}$, environmental impact characterization factor in impact category (m) for media (e, for example, water, air) to which chemical (i) is released to; H_i, impact rating value associated with chemical i (H_i', prior to normalization).

is important at this point to comment on missing data in the evaluation schemes. The WAR algorithm, for instance, does not include data for metal and metal compounds. The ratio of missing values to the total 72 chemicals covered in each of the selected schemes (i.e., SRSS, WAR, TRACI, RSEI and IRCHS) was determined to be 24%, 18%, 22%, 0%, and 7%, respectively.

To aggregate the overall potential impact of a specific chemical, we apply normalization and weighting steps [17]. For the chemical manufacturing industry, spatial weighting preferences are difficult to attribute due to the diverse manufacturing locations. The judgments of the user and stakeholders to make valuation decisions due to dissimilar midpoint environmental impacts categories also differ. Thus, weighting factors are set to unity equivalents. The relative priority of the different chemical releases according to the normalized rating value H_i associated with environmental impact potential of chemicals can then be obtained by the following equation:

$$H_i = \frac{H_i'}{\sum_i H_i'} \tag{1}$$

where

$$H_i' = \sum_m (\text{if } T_m \text{ is normalized}) \sum_n T_{i,m,e} \times S_{i,n,e} \tag{1-a}$$

H, impact rating value associated with chemicals (H', prior to normalization); T, environmental impact characterization factor within a specific evaluation scheme; S, absolute amount of release; i, chemicals; m, impact category within studied evaluation scheme; n, industry sector; e, media to which the emission is released.

As an example, Table 2 illustrates representative values for Eq. (1) as applied to the SRSS scheme. From the priority results, we find that the list of the “top ten” chemicals (i.e., the ten with the highest impact scores) derived from each of the five evaluation schemes represented a total of 34 chemicals, likewise the “top five” represented a total of 18 chemicals. By further evaluating the 34 chemicals, it is determined that, combined, they represent approximately 78% of the TRI releases, in terms of volume, from the chemical manufacturing industry; and they constitute approximately 81–98% of the potential environmental impact on the basis of the various evaluation schemes. Thus, the priority results for these chemicals, as derived from the five evaluation schemes (Fig. 2), lead to different conclusions to inform decision makers about the priority of chemicals. For example, carbon disulfide, ammonia and copper compounds are the three largest TRI releases from the chemical manufacturing industry, but if we use either SRSS or RSEI as the assessment tool, they fall into a relatively low priority. Although the relative priority of a given chemical may

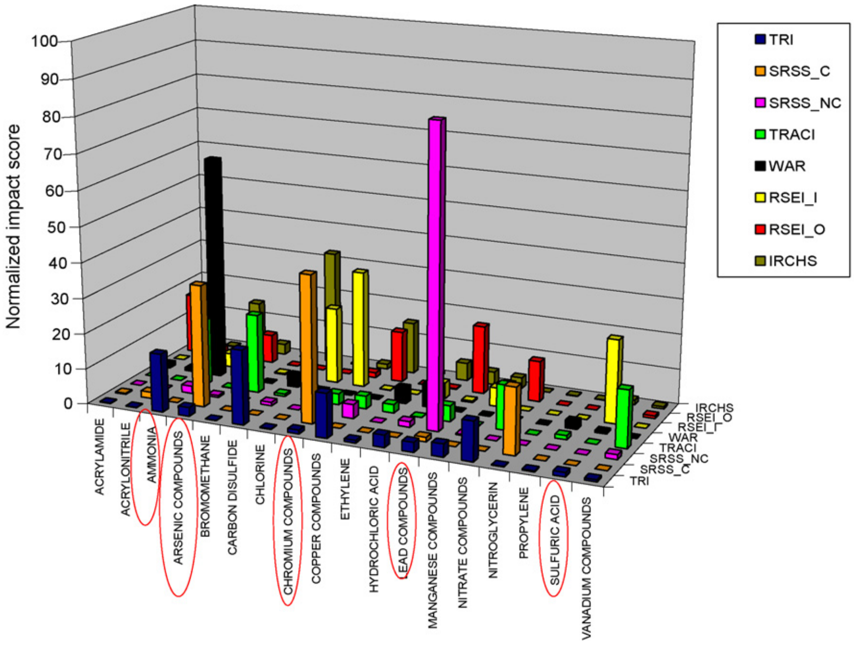

Fig. 2. Chemical priority based on release amount and impact potential to the environment. Low values are preferred. TRI: Toxic Release Inventory; SRSS_C: Scorecard Risk Scoring System Cancer Effect; SRSS_NC: Scorecard Risk Scoring System Non-cancer Effect; TRACI: Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts; WAR: Chemical Process Simulation for Waste Reduction Algorithm; RSEI_I: Risk-Screening Environmental Indicators Inhalation Effect; RSEI_O: Risk-Screening Environmental Indicators Oral Effect; IRCHS: Indiana Relative Chemical Hazard Score.

Table 3
Industry prioritization through five evaluation schemes.

n	i	$\sum_e S_{i,n,e}$	$\sum_m (\text{if } T_m \text{ is normalized}) \sum_e T_{i,m,e} \times S_{i,n,e}$						
NAICS	Chemical	TRI (total, kg)	SRSS_C	SRSS_NC	TRACI	WAR	RSEI_I	RSEI_O	IRCHS
325920	Ammonia	38.72	0	137.37	0.10	33.93	650.61	0	847.88
325920	Hydrochloric acid	74.30	0	891.65	0	30.49	6,687.40	0	2,726.97
325920	Total (D')	1352.79	870.69	1274.71	4.20	84.23	11,395.47	815.09	9,117.95
325920	D	2.41	13.22	0.08	2.58	0.69	0.29	0.00	0.65
325211	Methanol	36.32	0	2.88	0.02	3.22	14.34	4.44	897.06
325211	Nitrate compounds	27.18	0	0	0.14	0	0.00	8.43	0
325211	Total (D')	546.66	50.81	2225.98	4.46	359.79	44,643.80	133,297.12	14,222.65
325211	D	0.98	0.77	0.14	2.75	2.94	1.15	0.55	1.01

325920: explosives manufacturing industry sector; 325211: plastic materials and resin manufacturing industry sector; TRI: Toxic Release Inventory; SRSS_C: Scorecard Risk Scoring System Cancer Effect; SRSS_NC: Scorecard Risk Scoring System Non-cancer Effect; TRACI: Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts; WAR: Chemical Process Simulation for Waste Reduction Algorithm; RSEI_I: Risk-Screening Environmental Indicators Inhalation Effect; RSEI_O: Risk-Screening Environmental Indicators Oral Effect; IRCHS: Indiana Relative Chemical Hazard Score; D, impact rating value associated with industry sectors (D', prior to normalization); n, industry sector; i, industry sector; $\sum_e S_{i,n,e}$, total absolute amount of release of chemical i for the industry sector n, unit is kg; $\sum_m (\text{if } T_m \text{ is normalized}) \sum_e T_{i,m,e} \times S_{i,n,e}$, aggregated impact score for chemical i release in industry sector n for a specific evaluation scheme, dimensionless units.

vary depending on the evaluation scheme, it is important to note that, when taking into account the results from all five evaluation schemes, the highest impact is concentrated on several chemicals: ammonia, arsenic compounds, carbon disulfide, chromium compounds, lead compounds and sulfuric acid.

3.3. Priority industry sectors

Similar to the method described above to assign priority to each chemical based on impact potential, we obtain the priority at the industry sector level after applying each of the five evaluation schemes to weight, aggregate and normalize the relevant chemical data (see Eq. (2)).

$$D_n = \frac{D_n'}{\sum_n D_n'} \tag{2}$$

where

$$D_n' = \sum_i \sum_m (\text{if } T_m \text{ is normalized}) \sum_e T_{i,m,e} \times S_{i,n,e} \tag{2-a}$$

D, impact rating value associated with industry sectors (D', prior to normalization); T, environmental impact characterization factor within a specific evaluation scheme; S, absolute amount of release; n, industry sector; m, impact category within studied evaluation scheme; i, chemicals; e, media to which the emission is released.

Table 3 illustrates an example of the application of the procedure outlined in the equations above to prioritize industry sectors. As noted from the final results illustrated by Fig. 3, although the potential environmental impact for specific weighted chemicals varies within a wide range when comparing different evaluation schemes, the results at the industry sector level are much more

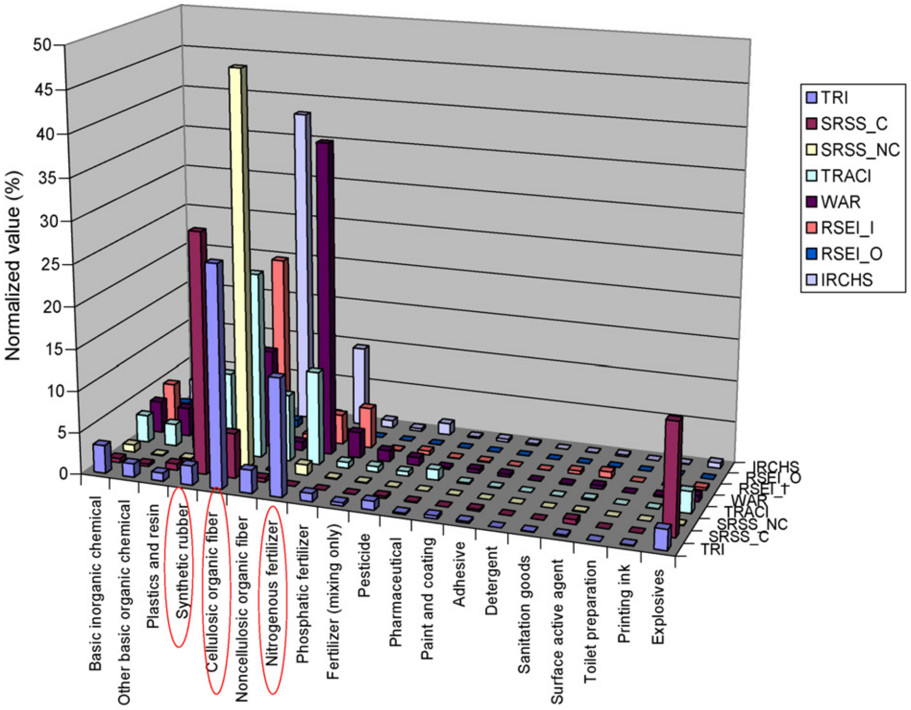

Fig. 3. Chemical manufacturing industry sector priority based on release amount and the impact potential to the environment. Low values are preferred.

concentrated in a few sectors. The highest priority industries, after aggregation, are the cellulosic organic fiber manufacturing industry, the nitrogenous fertilizer manufacturing industry, and the synthetic rubber manufacturing industry. Among these three sectors, only the cellulosic organic fiber manufacturing industry and the nitrogenous fertilizer manufacturing industry would have been captured as top priority sectors with the criterion of release amount per million dollars of output. The high volume releases generated by these industries are carbon disulfide and hydrochloric acid for the cellulosic industry, and ammonia and nitrate compounds for the nitrogenous fertilizer manufacturing industry. Evidently, the extent of potential environmental impact will be underestimated from quantity of release data alone. Thus, the incorporation of environmental impact evaluation with these schemes amplifies the necessity and priority of implementing environmental management measures. Furthermore, a look at the inter-correlation between priority chemicals and priority sectors reveals that the sectors having significant environmental impacts due to high volume releases and high priority chemicals should be targeted first by environmental management policy. The use of these chemicals in these sectors should be reduced and/or eliminated, for example, hydrochloric acid in the cellulosic industry. Proactive sustainability policy should also capture the sectors with relatively low emission volume but high environmental footprint due to select chemicals of concern, such as acrylonitrile and carbon tetrachloride in the synthetic rubber industry.

3.4. Supply chain impact

Further investigation into the environmental impact generated by each industry sector is implemented through the use of EIO-LCA. This tool allows for the assessment of both direct (i.e., during manufacturing) and total (including upstream activities along the supply chain) environmental impact [18]. Additional environmental aspects are also evaluated with the EIO-LCA tool: criteria air pollutant emissions (MT), energy usage (TJ) and global warming gas emissions (MT CO_2 equivalents). The results of this investigation (Fig. 4) indicate that when accounting for these other environmental aspects based upon quantity of emissions, for both *direct* and *total* (direct and upstream) impact for one million dollars worth of output within the same 19 chemical manufacturing industry sectors, the environmental indicators that represent upstream activities are dispersed on average and do not overwhelm the direct impact in general. We again notice the relatively high concentration of potential environmental impact in a few industry sectors, such as the nitrogenous fertilizer manufacturing industry (NAICS 325311), the inorganic chemical manufacturing industry (NAICS 325180), and the organic chemical manufacturing industry (NAICS 325190). The priority of the industry sectors changes due to upstream activities only when air pollutant emissions are considered.

Total environmental impact (including upstream activities) per industry sector was also derived with TRACI, as shown in Fig. 5. These results present different findings than those derived directly

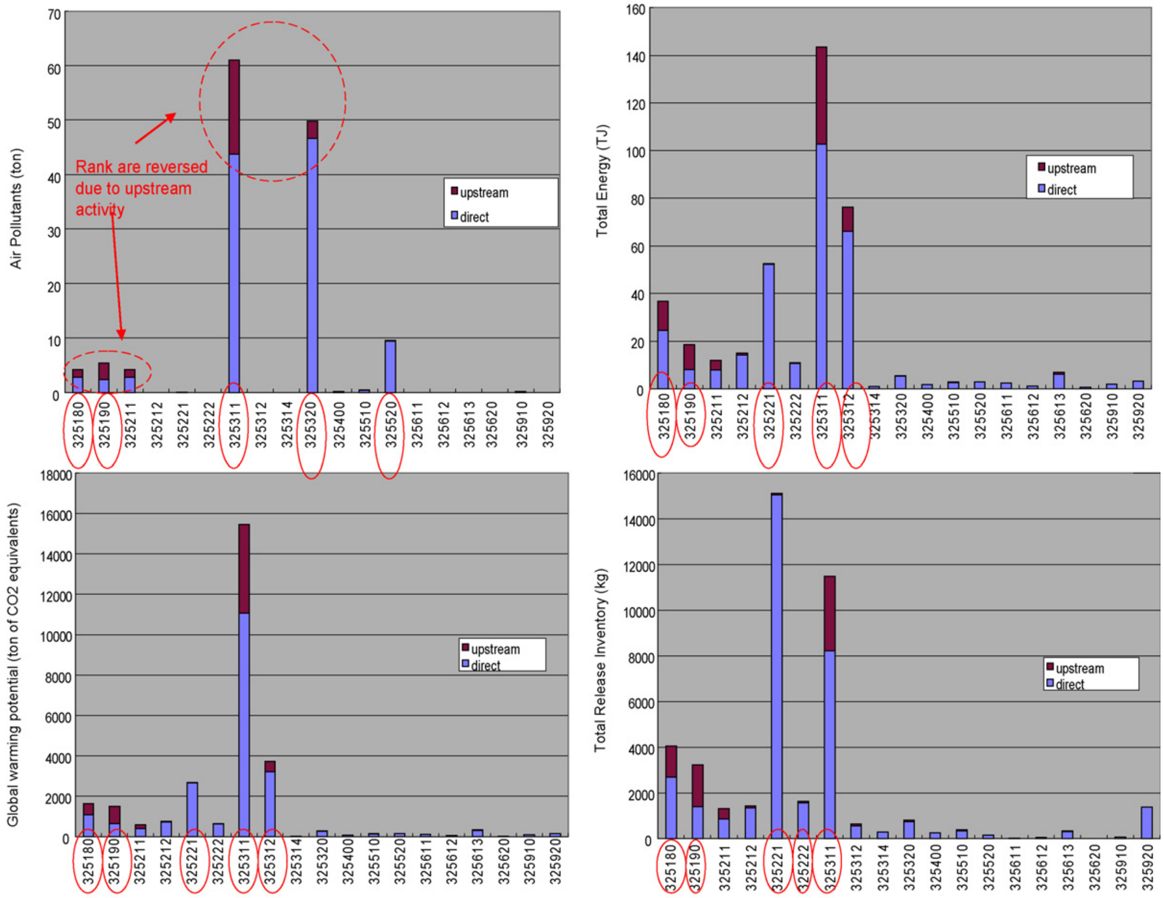

Fig. 4. The total supply chain, EIO-LCA derived, environmental release from the chemical manufacturing industry sectors (by six-digit NAICS code) in the United States. Low values are preferred. Data source: Economic Input–Output Life Cycle Assessment (EIO-LCA) Model. 325180: other basic inorganic chemical manufacturing industry; 325190: other basic organic chemical manufacturing industry; 325221: cellulosic organic fiber manufacturing industry; 325222: noncellulosic organic fiber manufacturing industry; 325311: nitrogenous fertilizer manufacturing industry; 325312: phosphatic fertilizer manufacturing industry; 325320: pesticide and other agriculture chemical manufacturing industry; 325520: adhesive manufacturing industry.

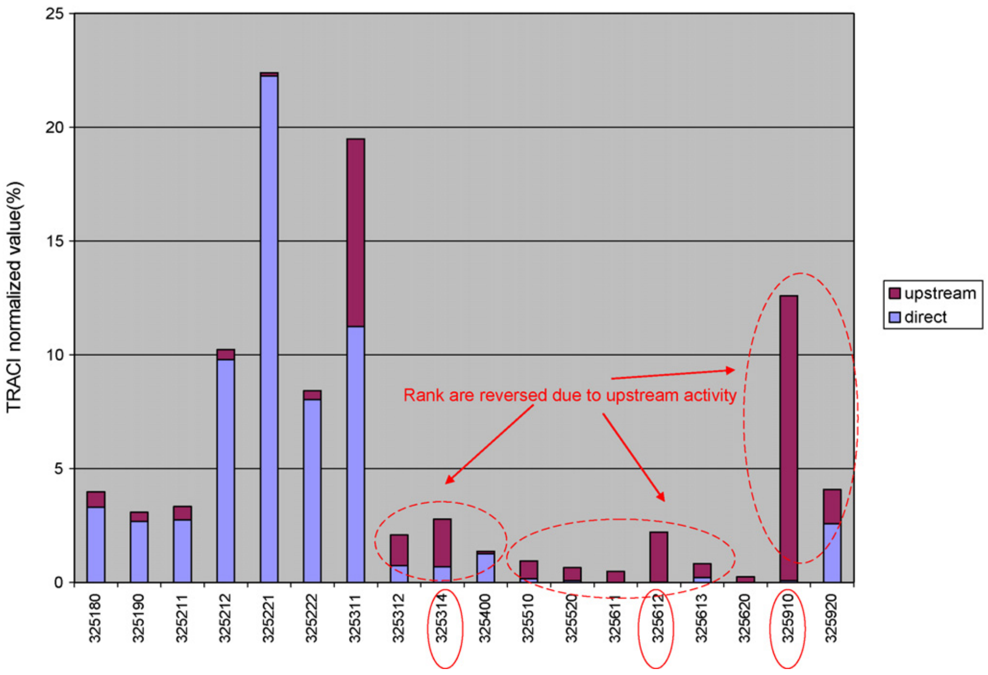

Fig. 5. The total supply chain, TRACI-derived, environmental impact in the chemical manufacturing industry sectors. Low values are preferred. NAICS codes are given in Fig. 1. 325314: fertilizer (mixing) manufacturing industry; 325612: Polish and other sanitation manufacturing industry; 325910: print ink manufacturing industry; TRACI: Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts.

from EIO-LCA in that the upstream activities contribute approximately 34% on average to the total impact and, for 9 out of the 19 industry sectors studied, the impact from the upstream activities overwhelm the direct impact. This difference in findings is due to the utilization of characterization factors in TRACI, whereas EIO-LCA is derived solely from quantity of emissions, as described earlier. It is important to note that some industry sectors, such as the printer ink manufacturing industry (NAICS 325910), the sanitation goods manufacturing industry (NAICS 325612), and the fertilizer (mixing) manufacturing industry (NAICS 325314), would likely be omitted from a priority list if only their direct impact was considered. Proactive regulations are needed, such as the Green Chemistry Initiative in California, which invokes life cycle thinking, so that the upstream supply chain impacts are also considered when prioritizing industry sectors. Furthermore, the above comparison indicates that important differences in prioritization of industry sectors can result not only when taking into account the potential environmental impact occurring along the supply chain but also that the utilization of multiple evaluation schemes allows the analysis to capture the sensitivity and inherent variability introduced by different evaluation tools.

4. Conclusions

In this study, we have demonstrated the utility of combining available U.S.-based environmental impact assessment tools to aid the prioritization of waste streams and industry sectors for policy making targeted at the chemical manufacturing industry and to help support pollution prevention decisions within the industrial setting. Further effort is required to achieve a better understanding of the environmental impact of chemicals and accountability of industry for the environmental performance of their products. By using comparative analyses, various evaluation schemes at the screening level can be used in combination with the conventional focus on absolute emissions and waste discharge information to provide further insight into on the potential adverse health and environmental impacts of chemical waste streams. We selected several representative evaluation schemes developed in the United States and utilized their chemical rating information to assess environmental performance on the basis of a common unit of economic activity. The focus was on the 19 industry sectors within the chemical manufacturing industry in the United States, although the method can be applied to any industry sector in any geographic region. In this method, the environmental impact data on select chemicals are extracted to provide a basis for quantitatively defining chronic health, and air/water/soil environmental impacts caused by these chemicals. The comparative analysis provides prioritization lists at several levels: hazardous chemicals in the waste stream, industry sector by aggregated environmental impacts, and industry sector by taking into account upstream activities along the supply chain. For the first two prioritization lists, although the relative rankings vary depending on the evaluation scheme used for the assessment, by combining the results from all the evaluation schemes, the highest priority items are easily identified, providing a fairly simple method to narrow the focus onto a few prioritized chemicals and industry sectors. If the indirect impact from upstream activities is included, the results have a relatively wider spread and lead to the prioritization of different industry sectors. A primary purpose of comparing these evaluation schemes is to raise the awareness of the regulatory community and industry about the variation and validity of the results provided by each of these schemes. Instead of choosing a single “best” evaluation scheme and criticizing the accuracy of the results, we highlight the value of using the assessment tools in combination to provide greater perspective in prioritizing hazardous substances and industrial sectors.

The results of this study also highlight, however, the disparities among these schemes and the consequential variation in results. Many previous studies have focused on the advantages/disadvantages of one assessment tool over another, of midpoint versus endpoint, of risk versus hazard [3,5–7,19]. For many stages in the decision making, such as for the present study, the need is not only to improve the existing individual tools, but also to improve the data quality and to use the collective experience to build a comprehensive picture.

Acknowledgements

Financial support has been provided by the University of California Toxic Substances Research and Teaching Program and the California Department of Toxic Substances Control.

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