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Summary

This study analyzes toxic chemical substance management in three U.S. manufacturing sectors from 1991 to 2008. Decomposition analysis applying the logarithmic mean Divisia index is used to analyze changes in toxic chemical substance emissions by the following five factors: cleaner production, end-of-pipe treatment, transfer for further management, mixing of intermediate materials, and production scale. Based on our results, the chemical manufacturing sector reduced toxic chemical substance emissions mainly via end-of-pipe treatment. In the meantime, transfer for further management contributed to the reduction of toxic chemical substance emissions in the fabricated metal industry. This occurred because the environmental business market expanded in the 1990s, and the infrastructure for the recycling of metal and other wastes became more efficient. Cleaner production is the main contributor to toxic chemical reduction in the electrical product industry. This implies that the electrical product industry is successful in developing a more environmentally friendly product design and production process.

Key Words: *toxic substances, logarithmic mean Divisia index, cleaner production, end-of-pipe ,U.S. manufacturing sector*

Introduction

The U.S. manufacturing sector has succeeded in reducing toxic chemical substance emissions since 1990. This is because U.S. manufacturing firms have managed toxic chemical substance emissions more strictly due to the revised Clean Air Act and the 33/50 program. The U.S. began to enforce pollution restriction laws in the 1940s and 1950s, and the Pollution Release and Transfer Register (PRTR) law was enacted in 1986 with a toxic release inventory (TRI). A few years later, the U.S. government began a unique environmental pollution reduction plan known as the 33/50 program, which was established in 1991. The 33/50 program targeted 17 priority chemicals, such as benzene and toluene and set a goal to reduce the release and transfer of these chemicals by 33% by 1992 and 50% by 1995 using a 1988 baseline. The primary purpose of the U.S. Environmental Protection Agency's (EPA) growing series of voluntary programs was to demonstrate the benefits of voluntary partnerships. Previous studies have supported the benefits of a voluntary approach to bring about targeted reductions more quickly than regulations alone (Khanna and Damon 1999; Gamper-Rabindran 2006). Meanwhile, Vidovic and Khanna (2007) find the opposite result and contest the claim that the 33/50 Program achieved reductions beyond what would been achieved in the absence of the Program.

The TRI is an information disclosure system for chemical substance release and transfer, and the 33/50 program involves voluntary toxic chemical emission reduction activities. Therefore, these two environmental policies do not force industrial firms to reduce emissions. However, firms have an incentive to reduce toxic chemical substance emission because the TRI information becomes a criterion for stakeholders to use in evaluating a firm's environmental activities and risk management for accidents with pollution (Cho et al. 2008). Additionally, firms that treat large quantities of highly toxic chemical substances become more proactive in managing toxic chemicals for risk management (Capelle-Blancard and Laguna 2010).

Environmental activity is defined as efforts and treatments aimed at conserving resources and reducing the environmental burden. Environmental activity can be divided into two major approaches. One is the end-of-pipe (EOP) approach, and the other is the cleaner production (CP) approach (Frondel et al. 2007).

The EOP approach is based on pollution removal using 'filters' in the last process, such as smokestacks or drains. Major EOP technologies include desulfurization and wastewater treatment. However, the EOP approach has several drawbacks. For instance, EOP treatments cause secondary environmental pollution problems, such as the generation of sludge waste during wastewater treatment, and they require enormous investment in equipment and expensive running costs. In addition, EOP treatments do not contribute directly to productivity improvements. Finally, because firms perceive the costs of EOP treatment as an additional investment for nonproductive activity, they do not usually have strong incentives for pollution abatement with the EOP approach.

The CP approach is defined as "the continuous application of an integrated preventive environmental strategy to processes, products, and services to increase overall efficiency, and reduce risks to humans and the environment" (UNEP 2006). A major CP approach is eco-design, in which the product design considers the environmental impacts of the product during its entire lifecycle. While the CP approach also requires investment in equipment, as does the EOP approach, running costs are not as expensive because the CP approach does not require filters and absorbent materials to remove pollutants (Kjaerheim 2005). Furthermore, because companies can save on intermediate material and labor due to an improved production process, cost reduction is another benefit (Zeng et al. 2010).

However, it is impossible for manufacturing companies to remove all environmental pollution by only applying the CP approach (Iovanna and Griffiths 2006). In short, companies need to apply both the EOP approach and the CP approach in a balanced way to achieve high environmental standards and company goals (Frondel et al. 2007). This idea implies that the framework of a pollution treatment approach is important to efficient toxic chemical management from both environmental and economic points of view.

Background and Objective

The U.S. Census Bureau published a list of pollution abatement costs and expenditures (PACE) in 2005 by industry type (U.S. EPA 2008). Table 1 summarizes the values of shipments, PACE, and PACE per shipment ratio by industry. The PACE per shipment ratio is high in the textile, paper, petroleum, chemical, nonmetallic mineral, and fabric metal industries. In contrast, the PACE per shipment ratio in the machinery, electrical equipment and transportation industries is lower than in the other sectors. The industries with high PACE per shipment ratios mainly incur their abatement costs for pollution treatment, which is essentially an EOP solution. In the meantime, industries with lower PACE per shipment ratios tend to incur abatement costs for recycling and disposal.

<Table 1 about here>

However, the technical difficulty associated with reducing emissions of toxic chemical substances differs between industries. It is clear that the required capital equipment and labor for reducing toxic chemical substances vary between industries because the chemical products consumed as intermediate materials are different. Several previous studies have applied the index approach to analyze the impacts of toxic chemical substance emissions (Yanagida et al. 2006; Lima et al. 2010). However, no previous studies have analyzed toxic chemical substance emissions management by focusing on the method of treatment. The objective of this study is to clarify how the U.S. manufacturing sector reduced toxic chemical substance emissions after 1991, focusing on the following five factors: end-of pipe treatment, cleaner production, transfer for further waste management, mixing of intermediate chemical materials, and production scale.

Data and Model

Data

Gross output data for each U.S. manufacturing sector came from the Bureau of Economic Analysis (U.S. Department of Commerce 2011), and while chemical substance data were obtained from the TRI database of the U.S. EPA (U.S. EPA 2011).

The data cover the eighteen years from 1991 to 2008[1]. This article focuses on three industrial sectors which include chemical products, fabricated metals, and electrical products industries[2]. Chemical industry is the typical industry which treats large amount of toxic chemical substances as intermediate materials (for example toluene and benzene). Fabricated metals industry has characteristics to use and emit toxic metal substances in their production process (for example copper and nickel). Meanwhile, electric product industry is processing and assembly type industry whose toxic chemical pollution intensity is relatively low respect to basic material type industry. This is because large amount of toxic chemical substances are used as intermediate materials in basic material industry, while electric product industry mainly uses toxic chemical substances for painting and bonding process but not as materials. Based on these industrial characteristics differences, we try to clarify the how U.S. manufacturing sector successfully reduced toxic chemical substances emission by comparing the result of three industries.

Expansion of the chemical list raised the number of chemicals and chemical categories reported to the TRI during our study period. To avoid the boundary problem, this study eliminates the chemical substances data that were added after 1991. Here, we focus on the toxic chemical substances which are regulated by two environmental policies which are RoHS directive[3] and 33/50 program to understand the effect of environmental policies. Additionally, we pick up the metal compound substances because metal substances can be recycled more easily than other substances. Thus, we categorized the toxic chemical substances into four groups: (1) object substances of the RoHS, (2) object substances of the 33/50 program, (3) metal and metal compounds, and (4) others[4]. Using this toxic chemical grouping, we can discuss the characteristic of each toxic chemical substance management separately.

This study used three variables for toxic chemical substances, including total releases (E), total off-site transfers for further waste management (T)[5], and on-site waste management (M)[6]. Two additional variables were created here. The first is the total amount of chemical substances generated (G), defined as: $G = E+T+M$. The other is waste transferred out of the facility (O), defined as: $O = E+T$. Y is the gross output data deflated to the 2005 price.

Model

There are many previous studies which use decomposition analytical framework. Most of them focus on the energy consumption or CO_2 emission. In these studies, independence of variables is important in decomposition analysis because interpretation becomes difficult in the case of interrelationships. However, the interrelationships would be valuable to the application of toxic chemical substance management. This is because toxic chemical substances emission is usually managed by applying both EOP treatment and CP treatment. In this case, the CP treatment absolutory affect the possible amount of EOP treatment. Thus, interrelationships can exist[7]. Therefore, decomposition analysis using only independent relationships between variables is inconsistent. To consider these problems, we propose a new decomposition application that is appropriate for toxic chemical substance management.

To decompose changes in toxic chemical substance emissions, the following five indicators are used: (1) end-of-pipe treatment (EOP), (2) cleaner production (CP), (3) transfer for further waste management (TR), (4) mixing of intermediate chemical materials (IM), and (5) production scale (PS).

We defined the CP indicator as G/Y, which represents the generation of toxic chemical substances per gross output. This indicator can be decreased by reducing the generation of toxic chemical substances while maintaining the same amount of production[8]. This reduction can be achieved by an improved production process and product design to reduce the input of intermediate chemical materials. Secondly, the EOP indicator is calculated as O/G, which represents the share of out of facility released in total toxic chemical substances generation[9]. This indicator can be reduced by increasing on-site waste management shares in total toxic chemical substances generation. We considered on-site waste management using three types of data, which are: (1) on-site recycling, (2) on-site energy recovery, and (3) on-site treatment. In considering these three methods of on-site waste management, we tried to understand why EOP changed from 1991 to 2008.

Thirdly, the TR indicator is calculated as E/O, which indicates the total emission amount share in released amount of outside of facility. This indicator can be reduced if the total amount of toxic chemical substances released decreases and off-site waste management increases. The TR indicator reflects how the industrial sector depends on off-site waste management. Off-site waste management mainly depends on the regional and social environmental capacity and equipment, such as recycling plants. We discussed the objective of transferring for further management using three data types, which are: (1) transfer to recycling, (2) transfer to energy recovery, and (3) transfer to treatment. In considering these three ways of off-site waste management, we tried to understand why the TR changed from 1991 to 2008.

Fourth, the IM indicator is defined as G_i /G, which reflects the variance in dependency on the input of the intermediate chemical material *i*[10]. Because the amounts of chemical substances generated strongly depend upon the input amounts of intermediate chemical materials, chemical substance generation is constructed as the input of chemical materials. In this sense, IM is treated as the input share of chemical substance *i* to the total input of chemical substances. Increases in IM imply that, as the share of chemical substance *i* increases, the relative importance of chemical substance *i* increases. In other words, IM explains the relative difficulty in decreasing the amount of *i* generated relative to other chemical substances[11]. The main factors responsible for changes in the IM indicator are (1) substitution of intermediate chemical material inputs and (2) relative technological innovation in the use of chemical materials.

Finally, the PS indicator shows the amount of change in production. Here, this study found it difficult to collect the product amount data by type of product. Therefore, the gross output deflated in 2005 price is used to determine the production amount. Generally, the amount of toxic chemical substances emitted depended upon the input amount of intermediate chemical materials. This is because the production scale became a factor in determining toxic chemical substance emissions. Here, the emission amount of chemical substances *i* (E_i) is decomposed as equation (1).

$$\mathrm{E}_i = \frac{\mathrm{E}_i}{\mathrm{O}_i} \times \frac{\mathrm{O}_i}{\mathrm{G}_i} \times \frac{\mathrm{G}_i}{\mathrm{G}} \times \frac{\mathrm{G}}{\mathrm{Y}} \times \mathrm{Y} = \mathrm{TR}_i \times \mathrm{EOP}_i \times \mathrm{IM}_i \times \mathrm{CP} \times \mathrm{PS} \tag{1}$$

We consider the emission change from t-1 year (E_i^{t-1}) to t year (E_i^{t}). By using equation (1), growth ratio of emission can be represented as follows.

$$\frac{\mathrm{E}_i^t}{\mathrm{E}_i^{t-1}} = \frac{\mathrm{TR}_i^t}{\mathrm{TR}_i^{t-1}} \times \frac{\mathrm{EOP}_i^t}{\mathrm{EOP}_i^{t-1}} \times \frac{\mathrm{IM}_i^t}{\mathrm{IM}_i^{t-1}} \times \frac{\mathrm{CP}^t}{\mathrm{CP}^{t-1}} \times \frac{\mathrm{PS}^t}{\mathrm{PS}^{t-1}} \tag{2}$$

We transform equation (2) to natural logarithmic function, then equation (3) is obtained[12].

$$\ln\mathrm{E}_i^t - \ln\mathrm{E}_i^{t-1} = \ln\left(\frac{\mathrm{TR}_i^t}{\mathrm{TR}_i^{t-1}}\right) + \ln\left(\frac{\mathrm{EOP}_i^t}{\mathrm{EOP}_i^{t-1}}\right) + \ln\left(\frac{\mathrm{IM}_i^t}{\mathrm{IM}_i^{t-1}}\right) + \ln\left(\frac{\mathrm{CP}^t}{\mathrm{CP}^{t-1}}\right) + \ln\left(\frac{\mathrm{PS}^t}{\mathrm{PS}^{t-1}}\right) \tag{3}$$

Multiplying both sides of equation (3) by $\omega_i^t = (\mathrm{E}_i^t - \mathrm{E}_i^{t-1})/(\ln\mathrm{E}_i^t - \ln\mathrm{E}_i^{t-1})$, we have equation (4) as follows[13].

$$\mathrm{E}_i^t - \mathrm{E}_i^{t-1} = \triangle\mathrm{E}_i^{t,t-1} = \omega_i^t\ln\left(\frac{\mathrm{TR}_i^t}{\mathrm{TR}_i^{t-1}}\right) + \omega_i^t\ln\left(\frac{\mathrm{EOP}_i^t}{\mathrm{EOP}_i^{t-1}}\right) + \omega_i^t\ln\left(\frac{\mathrm{IM}_i^t}{\mathrm{IM}_i^{t-1}}\right) + \omega_i^t\ln\left(\frac{\mathrm{CP}^t}{\mathrm{CP}^{t-1}}\right) + \omega_i^t\ln\left(\frac{\mathrm{PS}^t}{\mathrm{PS}^{t-1}}\right) \tag{4}$$

Therefore, changes in the emission of toxic chemical substance *i* ($\triangle\mathrm{E}_i$) is decomposed of the changes in TR (first term), EOP (second term), IM (third term), CP (fourth term,), and PS (fifth term). The term ω_i^t operates as additive weight estimated within LMDI framework. This decomposition technique of emission change factor is called logarithmic mean Divisia index (LMDI) developed by Ang et al. (1998). The LMDI has mainly been applied to energy studies (Charlita de Freitas and Kaneko 2011). Ang (2004) pointed out that the LMDI is the preferred method for decomposition analysis because of its theoretical foundation, adaptability, ease of use and result interpretation, and the lack of a residual term, which is generated by Laspeyres-type methodology.

Results

Table 2 and figures 1, 2, and 3 show the accumulated changes in emission amounts and ratios calculated by the LMDI model. Positive scores indicate emission increases, while negative scores imply emission decreases. Table 2 shows the accumulated amounts of change in the total absolute emissions and ratios from 1991-2008 by industry and chemical substance. Tables 3, 4, and 5 show the change in each on-site and off-site waste management ratio by type of chemical substance for 1991 and 2008, respectively[14].

In table 2, all three industries achieved a reduction in total toxic chemical substance emissions of more than 65% from 1991 to 2008. Of special note, the electrical product industry succeeded in decreasing toxic chemical substance releases by 92%. As for the emission reduction ratios by chemical substance, the three industries greatly reduced the emission amounts of chemical substances targeted by the 33/50 program. In the three industries, most of the chemical substances targeted by the 33/50 program were successfully reduced from 1991 to 2008, especially dichloromethane, toluene, and xylene. Meanwhile, metal and metal compound substances did not decrease, as compared to other types of chemical substances. Additionally, metal and metal compound emissions increased by 40% from 1991 to 2008 in the chemical product industry, while metal and metal compound emissions decreased in the other two industries. The reason for the increase in metal compound substance emissions was a rapid increase in the release of aluminum and manganese compounds in the chemical product industry. Increase of manganese compound is due to market demand growth of lithium-ion batteries made with lithium-manganese spinel cathodes which is used in personal computer and electric vehicle. Aluminum emission was rapidly increased from 2004, this is because aluminum is used as alternative material of lead which is restricted by RoHS. Because RoHS directive enforce to the entire electric product, paint product for electric product made in chemical industry is needed to care about lead containing. Object emissions of chemical substances from RoHS were reduced by 89% in the electrical product industry from 1991 to 2008, and the reductions in lead and chromium compound emissions were especially large.

Here, we discuss how toxic chemical substance releases decreased by focusing on the five factors responsible for emission changes. In the chemical manufacturing sector, the main factor responsible for the reduction in the emission of toxic chemical substances is EOP treatment. EOP treatments contributed 32% of the reduction in toxic chemical substance emissions from 1991 to 2008. EOP treatment had an especially strong negative effect on the object substances of the 33/50 program. However, the EOP treatment effect is positive for the object substances of RoHS and metal. One interpretation of the positive effect on RoHS substances is the effect of IM. The negative IM score of RoHS substances implies that the chemical manufacturing industry has shifted its intermediate input of chemical material from RoHS substances to other substances. Because this substantial change in input material decreased the generation of RoHS substances, the possible amount of on-site management decreased in the chemical manufacturing industry. IM score is quite different between all chemical substances and each type of chemical substances. The gap can be explained by absolute differences in the emission amounts, which are described in the first column of table 2. In table 2, 87% of the toxic chemical substance emissions were from others. This is because the scores were calculated based on all toxic chemical substances, which follow similar trends with others score in the chemical product industry.

However, the effect of IM is strongly positive for RoHS substances and metals in the fabricated metal industry. One interpretation of the positive IM effect on metal substances is that the ratio of metals to total toxic chemicals generated increased from 3.4% to 12.1%. This metal substance generation ratio increase is caused by both reduction of other chemical substances generation and increase of metal substances generation.

TR contributed to decreased toxic chemical emissions in all industries and for all types of chemicals without metal in the chemical product industry. One interpretation of this trend is that, due to the expansion of the environmental business market in the U.S., the GDP of waste management and remediation services in the U.S. increased from $29.3 billion U.S. to $37.8 billion U.S. This market expansion provided an incentive to design more efficient waste transfer systems and to build more efficient recycling and energy recovery plants (Psomopoulos et al. 2009; Damgaard et al. 2010). Because firms are able to more easily transfer their industrial waste to off-site plants, firms do not need to treat large amounts of industrial waste with on-site waste management. TR strongly contributed to reduce the emissions of RoHS substances in the fabricated metal and electrical product industries.

CP reduced all types of toxic chemical substance emissions in the three industries. This result implies that three industries succeeded in reducing toxic chemical substances by improving production processes and product designs to save on chemical material input. For example, Xerox Corporation[15] intended to re-design the printed wire board assemblies (PWBAs) to be manufactured with lead-free materials to offer a less toxic alternative product line while remaining competitive in the marketplace. As a result of that, Xerox Corporation was able to achieve an overall lead reduction in their raster optical scanner subassembly PWBAs from 2005 to 2008 of over 95 percent when normalized for total units produced (U.S. EPA homepage[16]).

<Table 2 about here>

Figures 1, 2, and 3 show the accumulated changes in emission reduction ratios using a 1991 baseline. The charted line shows the accumulated emission change ratios, and the bar chart shows the accumulated effects of each factor on emission reduction. The sum of the accumulated bars is equivalent to the charted line. By viewing each figure, one can distinguish between the characteristics of toxic chemical substance management by type of industry.

In figure 1, the chemical manufacturing industry succeeded in reducing the emission of toxic chemical substances by 55%, mainly due to the effects of TR, EOP, and CP from 1991-1994 when the 33/50 program was enforced. During this period, the chemical product industry reduced chemical substances targeted by the 33/50 program by 35%. Meanwhile, the effect of IM was relatively small in the chemical manufacturing sector. This is because share balance change of intermediate chemical material mix did not affect strongly to total toxic chemical substances emission change. Next, we will explain the contribution of the TR change using table 3[17]. In table 3, in 2008, all of the RoHS substances that were transferred off-site were recycled in the chemical product industry. Additionally, the off-site recycling ratio of 33/50 program substances increased from 1991 to 2008, even though the on-site recycling ratio decreased. These changes in the off-site recycling ratio imply that firms tended to promote a change in chemical waste recycling from on-site to off-site. One interpretation of this shift from on-site to off-site is that waste management technology progressed in U.S. recycling plants (Al-Salem et al. 2009). This technology change permitted more cost-effective and efficient treatment of chemical substance waste.

<Figure 1 about here>

<Table 3 about here>

Figure 2 illustrates the results from the fabricated metal industry. Toxic chemical substance emissions were comprehensibly reduced by TR, EOP, IM, and CP. The main contributor to emission reduction was CP. This means that the fabricated metal industry succeeded in reducing toxic chemical substance emissions through the development of more environmentally friendly product designs and more efficient production processes to reduce the input of chemical materials. The CP treatment mainly affected the object substances of the 33/50 program and other volatile organic compounds, such as toluene and benzene. Meanwhile, most of the TR treatments affected the object substances of RoHS and metal compounds, including chromium and lead. One cause for this trend could be the expansion of environmental businesses, especially more recycling plants for rare metals and metal compounds.

From 1991 to 1994, the fabricated metal industry reduced 33/50 program chemical substances by 37% by applying EOP treatment, even though the EOP scores for other chemical substances were positive or had a small effect on emission reductions. This result implies that the fabricated metal industry tried to reduce the 33/50 program emissions by applying EOP treatments from 1991 to 1994 when the 33/50 program was enforced. After 1994, the fabricated metal industry succeeded in reducing emissions by applying CP and IM.

IM contributed to the reduction in toxic chemical substances from 1994 to 1998. During this period, the generation amount of object substances from the 33/50 program and other volatile organic compounds decreased rapidly while the generation of metal compounds and RoHS substances increased. Because the effect of decreased shares of volatile organic compounds exceeded the effect of increased shares of metal compounds, the total IM effect became negative.

In table 4, the amount of on-site recycling in the fabricated metal industry increased from 1991 to 2008. The fabricated metal industry achieved a recycling ratio of more than 90% for both on-site and off-site RoHS and metal waste management. One interpretation of this high recycling ratio is that the international metal price increased from 1991 to 2008. This price growth provided an incentive to recycle RoHS and metal substances.

<Figure 2 about here>

<Table 4 about here>

In Figure 3, the main factors contributing to the decrease in emissions of toxic chemical substances in the electrical product industry were CP, IM, and TR. However, PS and EOP affected to increase emissions, especially PS, which increased emissions by 56%. One interpretation of the effects of CP and IM in the electrical product and machinery sector is that chemical substances are mainly used for paints and bonds during processing and assembly. Therefore, firms can reduce their toxicity by switching from highly toxic chemicals to less-toxic chemical materials. Currently, decreasing the use of toxic chemical substances is costly, but technological innovation reduces this cost and addresses several constraints such as bonding power and color quality. Additionally, TR exerted negative effects due to the maintenance of recycling plants for the metal slugs and waste plastic that it promotes (Al-Salem et al. 2009). Furthermore, one interpretation of the positive EOP score is that the amount of toxic chemical substances generated decreased by more than 80% from 1991 to 2008. This reduction in the amount generated caused a decrease in the possible amount for EOP treatment.

In table 5, the electrical product industry achieved a high recycling ratio both on-site and off-site; this is especially highlighted by the off-site RoHS and metal recycling ratio of 100% in 2008. Another significant change was the energy recovery ratio of the 33/50 program chemical substances. This change in energy recovery was caused by technological innovation in energy recovery equipment, which enabled the achievement of a high combustion ratio (Psomopoulos 2009).

<Figure 3 about here>

<Table 5 about here>

Conclusion and policy implication

This article analyzed how three U.S. industrial sectors succeeded in reducing toxic chemical substance emissions from 1991 to 2008. We focused on the following five factors: cleaner production, end-of-pipe treatment, transfer for further waste management, intermediate chemical material mixing, and changes in production. The chemical manufacturing sector was found to mainly reduce toxic chemical substance emissions by end-of-pipe treatments. Meanwhile, cleaner production and transfer for further management contributed to reduced toxic chemical substance emissions in the fabricated metal and electrical product industries because the environmental business market expanded in the 1990s, and the infrastructure for recycling metal and other waste became more efficient. The result of cleaner production implies that the fabricated metal and electrical product industries were successful in developing more environmentally friendly product designs and production processes.

We clarify the differences of toxic chemical substances management by industry type in U.S. manufacturing sector. Therefore, the environmental policies for toxic chemical substances management need to consider these differences in industrial characteristics, which are a function of intermediate materials used and available technology for emission reduction. Toxic chemical substances reduction with minimizing economic loss is important to achieve sustainable development. Thus, decision makers need to consider the industrial characteristics of toxic chemical substances emissions to set the appropriate emission standard for manufacturing industry.

Bui and Kapon (2012) show cleaner production plays important role to reduce toxic chemical substances emissions in U.S. manufacturing sector. They focus on analysis on industries as a whole and discussion on specific industry are not provided. EPA (2009) provides the information about change of toxic chemical substances emission amount by industry or but not available how each industry treat toxic chemical substances. In comparison, our new application of decomposition method to toxic chemical substance management can clarify how industrial firms and sectors treat toxic chemical substance emissions in more detail. This new decomposition application is helpful for decision-makers and corporate environmental manager to be able to understand the structure of toxic chemical substances emission change and suggest more effective environmental standards and management ideas.

Further research needs to investigate the different sectors such as non-manufacturing sector (for example hospitality industry) and household sector which discharge huge amount of solid waste. Additionally, each state has own environmental policy and standard for environmental protection. Thus, State-level analysis is also important to suggest appropriate toxic chemical substances management policy with considering each state's characteristics in U.S.

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Notes

1. Because waste management information has been added to the TRI by the Pollution Prevention Act of 1990 since 1991, we apply the TRI data from 1991 to 2008, even though TRI data were disclosed beginning in 1988.
2. Industry grouping is defined by the TRI, which follows the North American Industry Classification System code.
3. Restriction of the use of certain hazardous substances in electrical and electronic equipment (RoHS) directive regulates the electric product compound of toxic chemical substances which are cadmium, lead, mercury, hexavalent chromium, and specific brominated frame retardants. RoHS directive was passed in 2003 and were enforced in 2006. Under RoHS directive, electric products contained a level of toxic chemicals above a certain threshold cannot be sold in the European market.
4. Cadmium, chromium, lead, mercury, and nickel are included in more than two groups. To avoid double counting of these chemical substances, this study counts cadmium, chromium, lead, and mercury in the RoHS group and nickel in the 33/50 Program.
5. According to U.S. EPA definition, "Total off-site transfers for further waste management" is transfers to recycling, transfers to energy recovery, transfers to treatment, transfers to publicly owned treatment works and other off-site transfers, including transfers to disposal or other releases. An off-site transfer occurs whenever wastes are sent to a facility that is geographically or physically separate from the facility reporting under TRI. While off-site transfers do not result in environmental releases at the waste-generating facility, they can result in environmental releases at the off-site facility.
6. On-site waste management consists of on-site energy recovery, on-site recycling, and on-site treatment.
7. According to the TRI guidelines, on-site waste management data are estimated from the average combustion ratio multiplied by the amount of chemical substances used in equipment such as boilers and incinerators. Using this estimation method, reductions of toxic chemical substances generation by CP treatment decrease the amount of on-site waste management (U.S. EPA, 2002).
8. CP indicator also goes down if increasing production amount (revenue) while maintaining the generation of toxic chemical substances. This is happened due to (1) increase of production scale and cleaner production, and (2) increasing product value (price) by technological innovation. The latter case is mainly happened in processing and assembly industry such as electric

product industry. In our study, we cannot distinguish which reason make CP indicator decrease because it is hard to get the data about each product value change. This point is the limitation of our research. Based on these points, we consider CP indicator as cleaner production technology effect including product value change by product innovation.

9. It is more simple and appropriate to define the EOP indicator as E/G. However, under this definition, we can not discuss the differences of on-site and off-site water management effect. Here, we decompose E/G as E/G = (E/O)×(O/G). E/O represents the EOP effect of off-site waste management. While, O/G shows that EOP effect of on-site waste management. To distinguish the on-site and off-site waste management effect, we use O/G as EOP indicator and E/O as transfer for further waste management indicator.
10. *i* represents named chemical substances group such as object substances of the RoHS, and object substances of the 33/50 program.
11. In the case of a 10% decrease in the generation of chemical *k*, the IM score is positive if the total chemical substance generation decreases more than 10%. Meanwhile, the IM score of *k* is negative if the total chemical substance generation decreases less than 10%.
12. If there is a case of zero value in the dataset, which cause problem in the formulation of the decomposition because of the properties of logarithmic function. In order to solve this problem, the literature on the LMDI suggests replacing the zero value by a small positive number (Ang and Liu, 2007).
13. $\omega_i^t = 0$ if $E_i^t = E_i^{t-1}$.
14. Each ratio is calculated using on-site (off-site) recycling, on-site (off-site) energy recovery, and on-site (off-site) treatment data, all of which are provided by the TRI. Off-site treatment includes the amount of publicly owned treatment works. For example, the ratio of on-site recycling is calculated as the amount of on-site recycling divided by the amount of total on-site waste management.
15. Xerox Corporation is an electric product industry firm and produce color and black-and-white printers, multifunction systems, photo copiers, and digital production printing presses.
16. U.S. EPA, National Partnership for Environmental Priorities, http://www.epa.gov/osw/partnerships/npep/success/xeroxss.htm
17. Ratio is calculated as each on-site (off-site) waste management amount divided by total on-site (off-site) waste management amount.

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Table 1 Pollution Abatement Cost and Expenditures (PACE) in U.S. industry (Million U.S. $).

	(1)Value of shipments	(2)PACE	Ratio [(2)/(1)]	Breakdown of abatement cost			
				Treatment	Prevention	Recycling	Disposal
All industries	4,735,384	20,678	0.44%	52%	17%	8%	22%
Food	534,878	1,573	0.29%	55%	11%	7%	28%
Textile	41,149	221	0.54%	63%	7%	9%	21%
Paper	162,848	1,796	1.10%	60%	11%	7%	23%
Petroleum	476,075	3,746	0.79%	51%	35%	7%	8%
Chemical	604,501	5,217	0.86%	53%	16%	8%	24%
Plastics and rubber	200,489	503	0.25%	43%	16%	10%	32%
Nonmetallic mineral	114,321	696	0.61%	57%	18%	7%	18%
Primary metal	201,836	2,291	1.14%	54%	12%	10%	24%
Fabric metal	288,068	763	0.26%	46%	11%	12%	31%
Machinery	302,204	316	0.10%	34%	16%	11%	39%
Electrical equipment	373,932	624	0.17%	54%	9%	10%	27%
Transportation equipment	687,288	1,319	0.19%	45%	13%	12%	30%

Source: Pollution Abatement Cost and Expenditures 2005, U.S. Bureau of the Census

Table 2 Accumulate change of emission reduction amount and ratio by type of chemical substances from 1991-2008.

		Emission in 1991	Emission change	TR	EOP	IM	CP	PS
Chemical product	All (Amount)	1,408.77	-1,054.17	-355.07	-456.22	-65.96	-341.76	157.64
	All (Ratio)	100%	-75%	-25%	-32%	-5%	-24%	11%
	RoHS	2%	-59%	-23%	78%	-112%	-24%	22%
	33/50	8%	-82%	-50%	-60%	40%	-25%	12%
	Metal	4%	40%	7%	104%	-44%	-54%	26%
	Others	87%	-79%	-24%	-38%	-5%	-23%	10%
Fabricated Metal	All (Amount)	144.13	-93.36	-39.58	-11.29	-25.75	-55.87	36.39
	All (Ratio)	100%	-65%	-27%	-8%	-18%	-39%	25%
	RoHS	4%	-30%	-95%	7%	85%	-53%	26%
	33/50	43%	-91%	-11%	-52%	-22%	-26%	20%
	Metal	12%	-3%	-25%	9%	44%	-64%	34%
	Others	42%	-59%	-34%	32%	-41%	-43%	28%
Electric Products	All (Amount)	55.29	-50.82	-20.43	9.02	-13.31	-57.15	31.03
	All (Ratio)	100%	-92%	-37%	16%	-24%	-103%	56%
	RoHS	5%	-89%	-79%	11%	46%	-142%	75%
	33/50	47%	-98%	-19%	33%	-74%	-85%	46%
	Metal	6%	-35%	-27%	3%	136%	-347%	200%
	Others	42%	-93%	-53%	0%	1%	-85%	45%

* Amount shows absolute emission change (million pounds), Ratio shows emission change ratio (%)

Table 3 Change of waste management in chemical product industry in 1991 and 2008.

		Recycle		Energy recovery		Treatment	
		1991	2008	1991	2008	1991	2008
On-site waste management	All (Amount)	3,790.3	3,651.2	1,079.1	1,040.1	4,438.4	3,091.4
	All (Ratio)	41%	47%	12%	13%	48%	40%
	RoHS	34%	100%	0%	0%	66%	0%
	33/50	58%	83%	16%	4%	26%	13%
	Metal	86%	49%	0%	0%	14%	51%
	Others	39%	40%	11%	15%	50%	45%
Off-site waste management	All (Amount)	444.5	119.2	261.2	273.4	425.7	269.2
	All (Ratio)	39%	18%	23%	41%	38%	41%
	RoHS	69%	74%	1%	0%	31%	26%
	33/50	27%	19%	51%	54%	21%	28%
	Metal	21%	43%	1%	0%	79%	57%
	Others	44%	14%	16%	42%	41%	44%

*Amount shows absolute emission change (million pounds), Ratio shows share in waste management (%)

Table 4 Change of waste management by type of chemical substances in fabricated metal industry in 1991 and 2008.

		Recycle		Energy recovery		Treatment	
		1991	2008	1991	2008	1991	2008
On-site waste management	All (Amount)	180.6	88.6	9.8	5.8	228.3	97.5
	All (Ratio)	43%	46%	2%	3%	55%	51%
	RoHS	62%	100%	0%	0%	38%	0%
	33/50	82%	74%	3%	1%	15%	24%
	Metal	93%	90%	0%	0%	7%	10%
	Others	20%	4%	2%	6%	78%	90%
Off-site waste management	All (Amount)	238.9	359.2	9.4	4.3	55.9	27.1
	All (Ratio)	79%	92%	3%	1%	18%	7%
	RoHS	74%	94%	0%	0%	26%	6%
	33/50	54%	43%	24%	37%	21%	20%
	Metal	92%	94%	0%	0%	8%	6%
	Others	47%	85%	5%	4%	47%	11%

* Amount shows absolute emission change (million pounds), Ratio shows share in waste management (%)

Table 5. Change of waste management by type of chemical substances in electric product industry in 1991 and 2008.

		Recycle		Energy recovery		Treatment	
		1991	2008	1991	2008	1991	2008
On-site waste management	All (Amount)	130.2	3.9	1.1	0.5	175.3	32.9
	All (Ratio)	42%	10%	0%	1%	57%	88%
	RoHS	94%	100%	0%	0%	6%	0%
	33/50	98%	45%	0%	10%	1%	45%
	Metal	56%	100%	0%	0%	44%	0%
	Others	13%	5%	0%	0%	87%	95%
Off-site waste management	All (Amount)	76.7	40.6	6.3	4.5	24.1	8.1
	All (Ratio)	72%	76%	6%	9%	22%	15%
	RoHS	53%	92%	1%	0%	46%	8%
	33/50	65%	12%	15%	76%	20%	12%
	Metal	93%	94%	0%	0%	7%	6%
	Others	51%	23%	10%	30%	39%	47%

* Amount shows absolute emission change (million pounds), Ratio shows share in waste management (%)

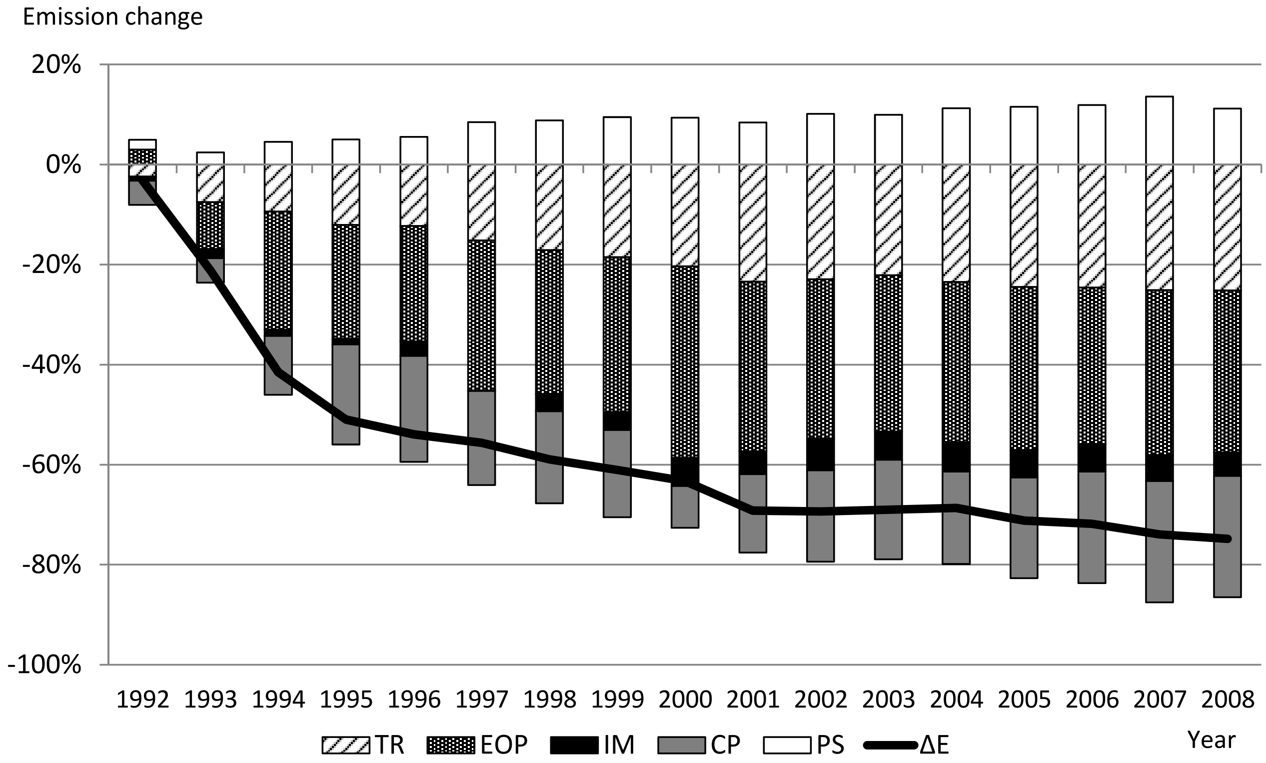

Figure 1 Accumulate change of emission reduction ratio in chemical product industry

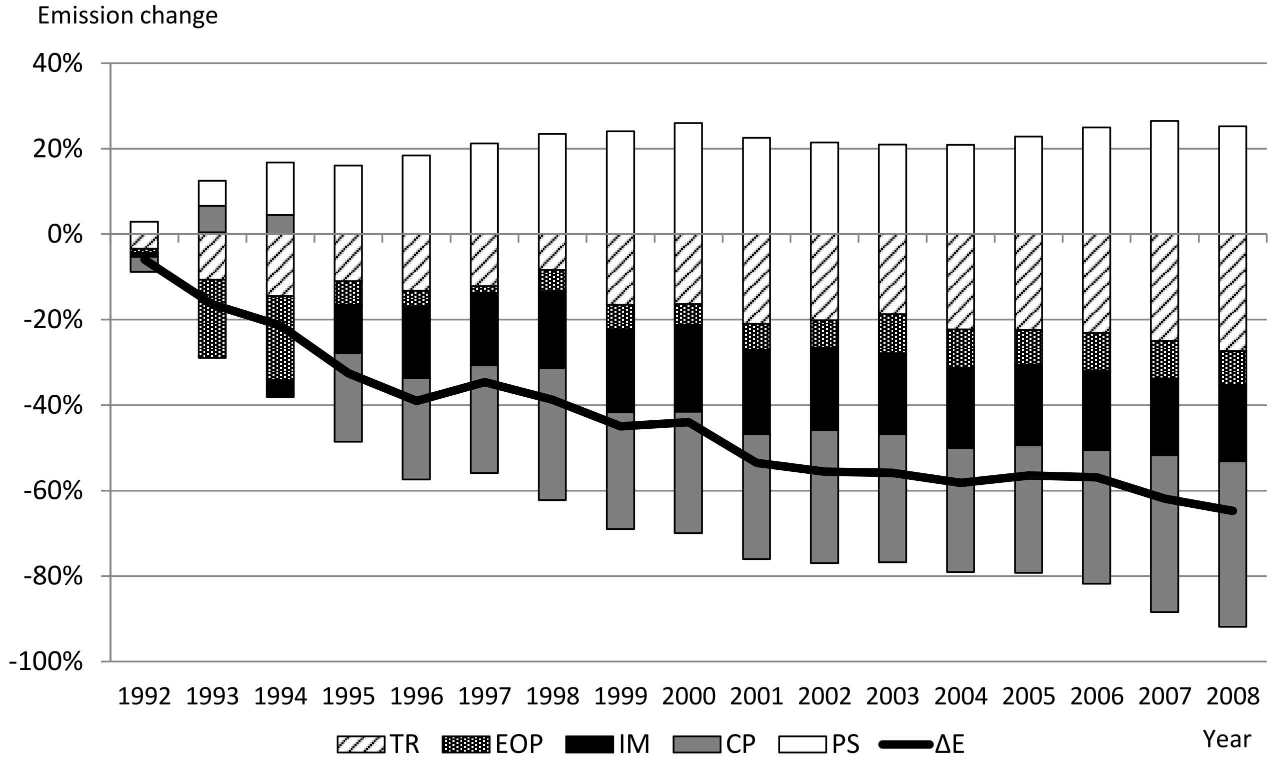

Figure 2 Accumulate change of emission reduction ratio in fabricated metal product industry

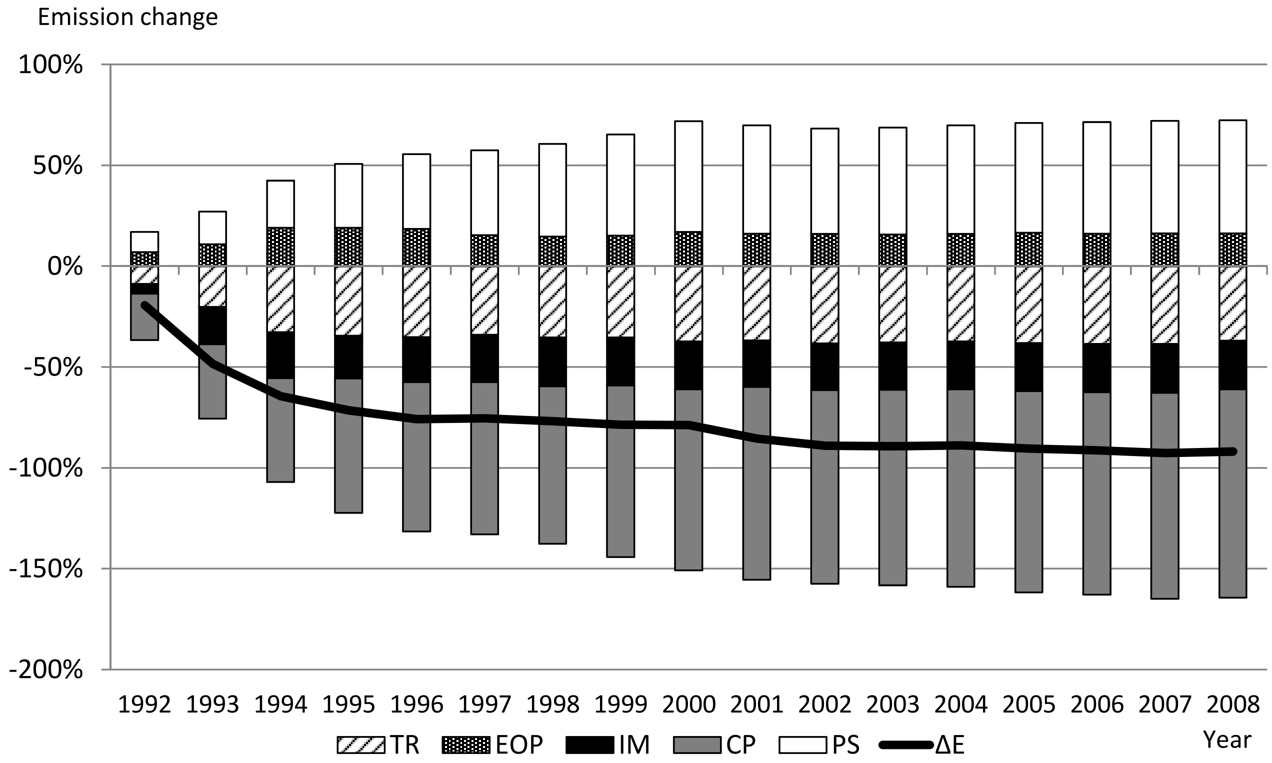

Figure 3 Accumulate change of emission reduction ratio in electrical product industry