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Factors influencing polychlorinated dibenzo-*p*-dioxin and polychlorinated dibenzofuran (PCDD/F) emissions and control in major industrial sectors: Case evidence from Shandong Province, China

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ABSTRACT

Analyzing determinants that influence polychlorinated dibenzo-*p*-dioxin and polychlorinated dibenzofuran (PCDD/F) emissions is helpful for decision-makers to find effective and efficient ways to mitigate PCDD/F emissions. The PCDD/F emissions and the contributions of the scale effect, structure effect and technology effect to emissions from eight main industrial sectors in 2006, 2008 and 2010 in Shandong Province, were calculated in this article. Total PCDD/F emissions in Shandong increased by 52.8% in 2008 (614.1 g I-TEQ) and 49.7% in 2010 (601.8 g I-TEQ) based on 2006 (401.9 g I-TEQ). According to the decomposition method, the largest influencing factor on PCDD/F emission changes was the composition effect (contributed 43.4% in 2008 and 120.6% in 2010 based on 2006), which was also an emission-increasing factor. In this case, the present industrial restructuring policy should be adjusted to control the proportion of production capacities with high emission factors, such as iron ore sintering and steelmaking and the secondary non-ferrous metal sector. The scale effect increased the emissions in 2008 (contributed 21.9%) and decreased the emissions in 2010 (contributed –28.0%). However, as a source control measure, the excess capacity control policy indeed had a significant role in emission reduction. The main reason for the technology effect (contributed 34.7% in 2008 and 7.4% in 2010 based on 2006) having an emission-increasing role was the weakness in implementing policies for restricting industries with outdated facilities. Some specific suggestions were proposed on PCDD/F reduction for local administrators at the end.

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Introduction

Polychlorinated dibenzo-*p*-dioxins (PCDDs) and polychlorinated dibenzofurans (PCDFs) are a group of related chlorinated organic compounds of unintentionally produced persistent organic pollutants (UP-POPs). Due to their persistent adverse effects on ecosystems and human health at trace levels, many countries have made efforts to reduce PCDD/F emissions, such as the application of best available techniques (BAT) and best environmental practices (BEP) (UNEP, 2006). Industrial activities, including waste incineration and secondary non-ferrous metal production, are the main PCDD/F emission sources (UNEP, 2001). In China, a preliminary estimation of PCDD/F emissions revealed that three kinds of industrial sectors contributed about 81% to the total emissions: ferrous and non-ferrous metal production, heat and power generation, and waste incineration (NIP, 2007). The remarkable growth and high detection values in sensitive areas of PCDD/F emissions posed major challenges to policymakers in China (Gao et al., 2011; Li et al., 2009; Sun et al., 2006). Thus, the reduction of PCDD/Fs emissions is an extremely urgent environmental issue for China.

In this context, understanding the determinants that influence PCDD/F emissions is helpful for decision-makers to find effective and efficient ways to reduce or eliminate them. Many studies have been carried out to identify the factors influencing PCDD/F emissions, such as studies on PCDD/F emission character analysis (Antunes et al., 2012), on the PCDD/F formation mechanism in industrial production processes (Dickson et al., 1992), and on technology improvements in production and air pollution control equipment (Kulkarni et al., 2008). However, most of those studies are microscopic studies. Besides these technical factors and mechanisms, macro factors, such as industrial scale and structure, can also affect PCDD/F emissions by changing industrial production or emission factors. Although some macro-level research has already been carried out to understand PCDD/F emissions control, such as the effects of energy conservation policy (Geng et al., 2010), of human activities (e.g., population and GDP) (Ren and Zheng, 2009), and of national strategies (Cheng and Hu, 2010; Lu et al., 2007; Lu and Giesy, 2005; Shi et al., 2005; Zhang et al., 2005), there is still a lack of knowledge on, for instance, how (much) these macro factors contribute to emission change and which policy instruments at regional level are suitable to control emissions. This work aims to fill this knowledge gap and attempts to provide some macro-level PCDD/F emission reduction suggestions to regional policy-makers in China.

In this article, an approach to find out the key factors influencing the PCDD/F emissions was provided, the prior control sectors were analyzed, and the effective policy instruments in emission control at the regional level were identified. PCDD/F elimination is a long and tough task for the Chinese government, since the variances of industrial emission sources distributed in different regions. The approach presented here offers useful lessons to other regions to design specific measures for PCDD/F emissions control.

1. Method and data

1.1. Decomposition analysis method

The economic activity scale of PCDD/F emission of industry, the industrial structure, and the conditions of production and

pollution control technology can directly or indirectly affect PCDD/F emissions. In order to assess the relative magnitude of these influencing factors, a decomposition analysis method, as initially proposed by Grossman (Grossman, 1995; Grossman and Krueger, 1991), was adopted in this article. Grossman and Krueger (1991) first suggested the decomposition analysis method and apply it to environmental studies. They decomposed the change of pollutant emissions into three mechanisms: scale effect, composition effect, and technology effect. This method has become a widely accepted tool for decomposition studies on national energy and environmental issues (Ang, 2004), and has been frequently used to decompose the contributions of various determinants, such as production activity (i.e., scale effect), industrial structure changes (i.e., composition effect), and pollutant emission ratio reduction or energy intensity reduction (i.e., technology effect), in the emission change analyses of CO₂, SO₂ and other air pollutants (Ang, 1994; Ang and Choi, 1997; Ang and Pandiyan, 1997; De Freitas and Kaneko, 2011; Diakoulaki and Mandaraka, 2007; He, 2010; Selden et al., 1999; Stern, 2002).

Although PCDD/Fs are different from CO₂ and SO₂ in many properties, all the variables used in the decomposition analysis method have nothing to do with pollutants' properties. Only the macro activities of industrial sectors and the total pollutants' emissions are considered, including the total production, production share, and emission intensity of the sector. Meanwhile, all the transformations of equations below are a purely mathematical process, which is not related to the pollutants' properties either. Therefore, it is reasonable to apply the decomposition analysis method to analyze the PCDD/F emission changes.

Three emission determinants are contained in Eq. (1): scale, composition and technology effects (Grossman, 1995).

$$E_t = \sum_{j=1}^n Y_t I_{j,t} S_{j,t} \quad (1)$$

where, E_t stands for the total emissions in year t ; $j = 1, 2, \dots, n$ represents the different sectors; Y_t is the total production of selected sectors in year t , which is equivalent to the sum of production of all the n sectors ($Y_t = \sum Y_{j,t}$); $I_{j,t}$ is the emission intensity of sector j in year t , and $S_{j,t}$ is the production share of sector j in year t . Eq. (1) is an identity, because of $I_{j,t} = E_{j,t}/Y_{j,t}$ and $S_{j,t} = Y_{j,t}/Y_t$.

The scale factor (Y_t) is positively related to pollutant emissions. Grossman (1995) notes that, under the condition of "all else being equal", an increase in production results in an increase in pollutant emissions. The "all else being equal" condition could be violated by changes in the industrial structure and changes in technology (De Bruyn, 1997; Grossman, 1995).

The composition change ($S_{j,t}$) in economic activities influences the proportion of high emission intensity sectors, which can positively or negatively affect emissions. If high emission intensity sectors grow faster than low emission intensity sectors, structural change results in an increase in emissions. Meanwhile, total emissions will grow faster.

With the application of more efficient production technology and more effective end-of-pipe technology, as well as changes in raw materials and fuel, the technology effect ($I_{j,t}$) can reduce emissions by a decrease in emission intensities (Emission/Production) (De Bruyn, 1997). That is to say, the technology effect in this article can be defined as a broad concept, as it includes all kinds of technical interventions that could decrease PCDD/F emission intensity (He, 2010). These could be, for instance, (1) improvement in energy use efficiency to make the combustion process a better condition in which PCDD/Fs can be destroyed; (2) application of effective air pollution control equipment; (3) substituting high-chlorine raw materials with medium or low-chlorine ones; (4) adjustments in production temperature to avoid the optimal temperature interval for PCDD/F generation.

Differentiating Eq. (1) with respect to time gives Eq. (2),

$$E'_t = \sum_{j=1}^n I_j S_j Y' + \sum_{j=1}^n Y S_j I'_j + \sum_{j=1}^n Y I_j S'_j. \quad (2)$$

Eq. (2) presents the continuous decomposition of the emission ratio into scale, structural and technological effects. For discrete data available in years 0 and T, integrating from 0 to T, Eq. (2) can be expressed as Eq. (3):

$$\begin{aligned} \int_0^T E'_t dt &= \int_0^T \sum_j I_j S_j Y' dt + \int_0^T \sum_j Y I_j S'_j dt + \int_0^T \sum_j Y S_j I'_j dt \\ &= \Delta E_{\text{sca}} + \Delta E_{\text{str}} + \Delta E_{\text{tec}} + D = \Delta E + D \end{aligned} \quad (3)$$

where, ΔE_{sca} reflects the scale effect, ΔE_{str} reflects the structural effect, and ΔE_{tec} reflects the technology effect. Unfortunately there is no unique solution to the integral of Eq. (3), which is known in the literature as the integral path problem (Liu et al., 1992); and there is a residual term D left. The discrete approximation of Eq. (3) used in this paper comes from Ang's Divisia index method, which contains two discrete approximation methods to get the integral, called parametric Divisia methods (PDM1 and PDM2) (Ang, 1994). Using PDM2, the changes posed by scale, structural and technology between the years 0 and t can be expressed as:

$$\Delta E_{\text{sca}} = [I_0 + \alpha(I_t - I_0)](Y_t - Y_0) \quad (4)$$

$$\Delta E_{\text{str}} = \sum_j [I_{j,0} Y_0 + \beta_j (I_{j,t} Y_t - I_{j,0} Y_0)] (S_{j,t} - S_{j,0}) \quad (5)$$

$$\Delta E_{\text{tec}} = \sum_j [Y_{j,0} + \tau_j (Y_{j,t} - Y_{j,0})] (I_{j,t} - I_{j,0}) \quad (6)$$

where, $0 \leq \alpha, \beta_j$ and $\tau_j \leq 1$, $I_t = E_t/Y_t$.

Choosing different values for parameters α , β_j and τ_j in Eqs. (4)–(6) means defining different integral paths in the Divisia indices (Ang, 1994; Ang and Lee, 1994). The parameter values can also be regarded as weights assigned to the changes in the relative variables in year 0 and t in the decomposition (Ang, 1994; De Bruyn, 1997). According to Ang (1994), PDM2 is used with $\alpha = \beta_j = \tau_j = 0.5$. Thus, Eqs. (4)–(6) are presented as Eqs. (7)–(9):

$$\Delta E_{\text{sca}} = 0.5(I_0 + I_t)(Y_t - Y_0) \quad (7)$$

$$\Delta E_{\text{str}} = 0.5 \sum_j (I_{j,0} Y_0 + I_{j,t} Y_t) (S_{j,t} - S_{j,0}) \quad (8)$$

$$\Delta E_{\text{tec}} = 0.5 \sum_j (Y_{j,0} + Y_{j,t}) (I_{j,t} - I_{j,0}). \quad (9)$$

1.2. Study area

Shandong Province, an economically advanced coastal province in Eastern China, plays an important role in the industrial development of China. The industrial gross output value of Shandong was among the top three in China from 2006 to 2010, and the industrial output proportion was always above 10% (NBSC, 2007–2011). Shandong had almost all the industrial PCDD/F emission sources (NIP, 2007), and led in the production of many key PCDD/F emission sectors in China, such as steel and coke production (NBSC, 2007–2011). Nevertheless, the industrial structure in Shandong was not balanced, and backward production facilities, which are prone to high emission levels, still dominated much in many heavy polluting sectors in the years studied (GSD, 2011a).

Many studies of PCDD/F concentration in sediments and mussels from coastal sea (Pan et al., 2008), in human milk (Sun et al., 2010), in marine and lacustrine sediments (Pan et al., 2010), and in shell fish (Shen et al., 2009) reveal that Shandong has suffered from high levels of PCDD/F pollutions for many years. As a province with the 2nd longest coastline in China and located close to South Korea (across the Yellow Sea), POP concentrations in this region have become a hot topic (Naile et al., 2011). Therefore, figuring out strategies on how to reduce PCDD/F emissions in Shandong Province is urgently needed.

1.3. Data description

In order to accomplish PCDD/F emission inventory, national investigations of POP emission sources were conducted by the Ministry of Environmental Protection (MEP) of China with base years 2006 and 2008 (MEP, 2009). Since 2011, the system of statistical report on POPs has been established, which requires environmental protection bureaus and industries reporting POP data annually (MEP, 2011). The information on the production and emission factor of every industrial sector with different scales and technology in this paper was obtained from such a database of the Environmental Protection Bureau of Shandong Province (Table S1 in Supporting materials). The total emission factors involve the emissions to all the environmental media and in products and residues (Table S2). The sectoral and total PCDD/F emissions were calculated by Eq. (10), and the results were presented in Table 1.

$$E = \sum_j E_j = \sum_j EF_j \times P_j \quad (10)$$

where, EF means the emission factor, E means the total emissions and E_j means the emissions of sector j; P_j means the production of sector j.

Shandong had 13 sectoral categories out of a total of 17 sectoral categories identified in the national survey of POPs.

Table 1 – Total facility amount, production, PCDD/F emissions and emission intensity of industrial sectors in Shandong province in 2006, 2008 and 2010.

Sector	Facility amount			Production ($\times 10^4$ ton)			PCDD/F emissions (mg I-TEQ)			Emission intensity ($\mu\text{g I-TEQ/ton}$)		
	2006	2008	2010	2006	2008	2010	2006	2008	2010	2006	2008	2010
Waste incineration	61	78	47	65.63	119.63	210.22	26399.79	29323.50	83114.79	40.23	24.51	39.54
Pulp and paper	156	151	78	543.20	598.47	366.15	20145.58	23297.92	11010.86	3.71	3.89	3.01
Cement production	586	410	40	8774.51	7736.02	1964.62	52647.07	46416.10	11787.72	0.60	0.60	0.60
Iron ore sintering	54	71	72	4882.48	6670.69	8523.91	170749.49	209808.30	202747.10	3.50	3.15	2.38
Steelmaking	78	95	85	3841.17	4563.96	4984.40	71971.28	88646.45	96737.30	1.87	1.94	1.94
Coke production	110	106	81	2592.91	2689.69	2259.07	27430.99	27222.55	17343.61	1.06	1.01	0.77
Foundries	421	429	426	177.20	521.34	384.18	9475.76	43540.84	23605.68	5.35	8.35	6.14
Secondary non-ferrous metals production	23	29	29	20.51	29.42	33.12	23071.30	145868.45	155483.20	112.51	495.87	469.39
Total	1489	1369	858	20897.60	22929.21	18725.67	401891.26	614124.11	601830.25	–	–	–

PCDD/F: polychlorinated dibenzo-*p*-dioxins and polychlorinated dibenzofuran.

Because of much lower PCDD/F emissions, hot-dip galvanizing, 2,4-dichlorophenoxyacetic acid (2,4-D), *Chlorobenzene* and polyvinyl chloride (PVC) production were excluded. Meanwhile, since this paper focused only on industrial activities, the crematoria sector was also omitted despite the fact that it is a main emission source (NIP, 2007). In this case, 8 sectors were taken into consideration, including waste incineration, pulp and paper, cement production, iron ore sintering, steelmaking, coke production, foundries and secondary non-ferrous metal production, and a total of 1489, 1369 and 858 facilities in 2006, 2008 and 2010 were analyzed (Table 1).

2. Results

2.1. PCDD/F emissions and decomposition

Total PCDD/F emissions in Shandong increased by 52.8% in 2008 (614.1 g I-TEQ) and 49.7% in 2010 (601.8 g I-TEQ) based on 2006 (401.9 g I-TEQ) (Table 1). Among the top three emission sources, the iron ore sintering (IS) and steelmaking (ST) sectors were always included, and the sum of them took about 50% of the annual total emissions (Fig. 1), which indicated that the sectors with high emission constantly

dominated total emissions. Moreover, the industrial emissions varied significantly from sector to sector. For instance, as the highest emission sector in 2006, the iron ore sintering sector released 170.7 g I-TEQ, which was 18 times higher than the emissions from the foundries sector (9.5 g I-TEQ) (Table 1). The emissions of the same industrial sector were not constant either. The emissions in the cement and coking sectors decreased annually, and those of the cement sector fell significantly between 2008 (46.4 g I-TEQ) and 2010 (11.8 g I-TEQ) (Table 1). The secondary non-ferrous metal industry went through a rapid increase, with its 2008 emission (145.9 g I-TEQ) 6 times more than the 2006 level (23.0 g I-TEQ) (Table 1). Emissions in paper and pulp and foundries increased from 2006 to 2008 but declined by 2010 (Table 1). The PCDD/F emission decomposition results calculated according to Eqs. (7)–(9) and based on the year 2006 are shown in Table 2. The relatively small residuals (0.5% in 2008 and –0.3% in 2010) revealed the high efficiency of the decomposition method (Table 2), which supported our choice of method and derivation of the equations. The most important contributor to the PCDD/F emission changes was composition change. It could be seen that the structure and technology effects were always the factor of increasing emissions (positive values), while the scale effect showed mixed signs (positive and

Fig. 1 – Percentage of sectoral PCDD/F emissions in 2006, 2008 and 2010 in Shandong Province. WI: waste incineration; PP: pulp and paper; Ce: cement production; IS: iron ore sintering; ST: steelmaking; Co: coke production; F: foundries; SN: secondary non-ferrous metal production; PCDD/F: polychlorinated dibenzo-*p*-dioxins and polychlorinated dibenzofuran.

Table 2 – Contributions of scale, composition and technology effects to PCDD/F changes in 2008 and 2010 based on 2006.

Year	Scale effect		Composition effect		Technology effect		Total ΔE (g)	Actual $\Delta E'$ (g)	Residual
	ΔE_{sca} (g)	Percentage	ΔE_{str} (g)	Percentage	ΔE_{tec} (g)	Percentage			
2006	–	–	–	–	–	–	–	–	–
2008	46.7	21.9%	92.6	43.4%	74.0	34.7%	213.3	212.2	0.5%
2010	–55.8	–28.0%	240.5	120.6%	14.7	7.4%	199.4	199.9	–0.3%

PCDD/F: polychlorinated dibenzo-*p*-dioxins and polychlorinated dibenzofuran.

negative values) in the years studied (Table 2). The negative value of scale factor in 2010 (–28.0%) slowed the rate of emission increase, resulting in a slight emission decrease in 2010 compared with 2008 (Table 2).

2.2. Scale effect on PCDD/F emission change

Pollution is regarded as a byproduct of industrial production activities. Emissions would usually grow as the economy grows if the industrial structure and technology remain the same, and this effect may be neutralized by the two others (Grossman, 1995). It is not hard to understand that when total production (including waste processed) increased 9.7% in 2008 compared with that in 2006, the scale effect led to higher emissions (i.e., $\Delta E_{\text{sca}} > 0$) (Tables 1 and 2). With a series of effective energy saving and pollution discharge reduction policies implemented in 2007, the production of some sectors (e.g., cement industry) declined resulting from the closure of outdated production sites or elimination of small-scale energy inefficient factories (Geng et al., 2010). With a 10.4% decline of total production in 2010 compared to that in 2006 (Table 1), the scale effect led to a decrease in PCDD/F emissions (–28.0%) (Table 2), but was offset by emission increases brought about by structural effects. As a result, total emissions in 2010 still increased compared with 2006 (Table 1). Thus, the scale effect is consistent with the total industrial production changes.

2.3. Composition effect on PCDD/F emission change

The generally positive values of composition effect pointed out that it was an emission-increasing factor for Shandong Province (Table 2). It was also the factor with the largest influence, contributing 43.4% and 120.6% to the total emission change in 2008 and 2010 based on 2006, respectively (Table 2). Earlier, analysts suggested that such results may be common for a country in its early phase of industrialization, perhaps owing to the non-balanced and inefficient changes in early industrialization processes (He, 2010). Different industrial sectors have various PCDD/F emission factors, and show very large variances. For example, the emission factor of the secondary copper industry (100–1400 μg I-TEQ/ton) is hundreds of times larger than that of the cement industry (0.6 μg I-TEQ/ton) (Table S2). When industrial structure adjustments result in a faster growth in production output of sectors with relatively high emission factors, the composition changes would increase PCDD/F emissions. That could partly explain why total production in 2010 was reduced compared with that in 2006, but PCDD/F emissions still increased (Table 1). Therefore, the percentage of the high-emission industrial sector can affect the total PCDD/F emissions significantly.

2.4. Technology effect on PCDD/F emission change

It is uncommon for the technology effect to be an emission-increasing factor on PCDD/Fs (cf. (He, 2010)). Following the definition of the decomposition analysis method, the emission intensity (Emission/Production) represents the technology effect. According to the sectoral PCDD/F emission data, the fluctuations of emission intensity of each sector varied very much from 2006 to 2010 (Table 1). For example, the average PCDD/F emission intensity of the secondary non-ferrous metal industry increased sharply from 112 to 496 μg I-TEQ/ton from 2006 to 2008, and decreased to 469 μg I-TEQ/ton in 2010 (Table 1). However, the waste incineration sector presented an opposite trend (Table 1). There were also some sectors that always presented a slight declining trend in the average of PCDD/F emission intensity, such as the iron ore sintering sector and coking sector (Table 1). The decrease of emission intensity in those sectors can explain why the growth of the contribution of the technology effect to PCDD/F emission in 2010 (7.4%) was much less than that in 2008 (34.7%) (Table 2). Hence, the technology effect to the emission change can be positive or negative.

3. Discussion

3.1. Influence of excess capacity reduction policy on PCDD/F emissions

There are many kinds of policies affecting the scale of industrial sectors, of which, policies on the control of excess capacity have the most direct roles. The unreasonable production expansion has caused excess capacity problems in some sectors, such as the cement and steelmaking industry (SCC, 2006). The excess capacity in these sectors not only consumed lots of natural resources and impeded a healthy market development, but also put pressure on PCDD/F emissions owing to the large increase in production (i.e., scale effect). Since the 10th five-year plan period (2001–2005), the Chinese government has taken many steps to control the excess capacity in steelmaking, cement industries, etc. More national policies were published in the 11th five-year plan period (2006–2010). The policies used to eliminate excess capacity usually consist of a combination of policy instruments, such as restraining newly established projects and phasing out backward capacity.

The notice of accelerating the structure adjustment of industries with excess capacity (SCC, 2006) and the suggestions for restraining parts of sectors with excess capacity and redundant building projects to lead a healthy industrial development (SCC, 2009) played significant roles in decreasing

excess capacity in Shandong. For instance, the production of the cement sector decreased 57.8 million tons between 2008 (77.4 million tons) and 2010 (19.6 million tons) (Table 1). Since the emission intensity of the cement industry was almost the same from 2008 to 2010, a significant decrease of PCDD/F emissions was presented from 2008 (46.4 g I-TEQ) to 2010 (11.8 g I-TEQ) (Table 1). Therefore, there is no doubt that the main reason for emission change in the cement sector is the vast fluctuation in cement production.

Controlling the scale of PCDD/F emission sectors is a source control method. Some main PCDD/F emission sectors are exactly the industries mentioned in the national policies on control of excess capacity, such as steelmaking and coke sectors (SCC, 2009). Thus, implementing these policies to decrease the total industrial production would have a synergetic and significant role in the PCDD/F reduction.

3.2. Influence of structure adjustment policy on PCDD/F emissions

China has gone through several stages of industrial structure adjustment since the reform and opening-up policies implemented in the late 1970s (NDRC, 1998). With the issuing of the tentative regulation of improving industrial structure adjustment (NDRC, 2005b) and the first edition of the guidance catalogue of industrial structure adjustment (NDRC, 2005a), strong guidance was given to sectors such as the iron and steel, coke and secondary non-ferrous metal sectors. Local governments also set specific objectives and implementation measures. At the beginning of the 11th five-year plan period, Shandong Province formulated suggestions for accelerating elimination of outdated production capacity to upgrade the industrial structure (SDEITC, 2006).

Shandong achieved major progress in industrial structure adjustment and upgrading (SDEITC, 2012). Nevertheless, with respect to PCDD/F emissions, the structure change decreased the proportion of production in the cement sector (42.0% in 2006, 33.7% in 2008 and 10.5% in 2010), which has a low emission factor, and meanwhile increased the proportion of some sectors with relatively high emission factors, such as the iron ore sintering

(23.4% in 2006, 29.1% in 2008, and 45.5% in 2010), steelmaking (18.4% in 2006, 19.9% in 2008, and 26.6% in 2010) and secondary non-ferrous metal (0.1% in 2006, 0.1% in 2008, and 0.2% in 2010) sectors (according to the data in Table 1). With a 68.1 million ton production decrease in the cement sector, the PCDD/F emission reduction from 2006 to 2010 was about 40.9 g I-TEQ, much less than the 132.4 g I-TEQ increase in emissions from the secondary non-ferrous metals sector, which had only a 0.13 million ton production growth in the same period (Table 1). This implies that emission reductions in sectors with low emission factors are easily neutralized by production increases in sectors with high emission factors. Obviously, although these industrial structure adjustment policies achieved great environmental and energy benefits (SDEITC, 2012), they were not effective for PCDD/F control. It is therefore important to give special consideration to the proportions of those sectors with high PCDD/F emissions in the industrial structure adjustment process.

3.3. Influence of outdated capacity elimination policy on PCDD/F emissions

The amount of outdated facilities and technologies can influence the emission intensity, which is called the technology effect in this paper. The national and Shandong governments have promulgated many regulations and policies to improve industrial production technology and pollution control facilities. The policy instruments included elimination of outdated facilities, encouraging the application of state-of-the-art technology, and mandatory adoption of bag filters in certain sectors. Many projects were carried out to reduce air and water pollution emissions per production or per gross industrial output value (GSD, 2011b). Also, the operational costs for pollution control facilities in some key sectors increased annually in Shandong Province (SDSB, 2000–2011). On this occasion, the conventional pollutant emission per production had a decreasing trend, such as SO₂ emissions per production of steelmaking, and dust emissions per production of cement (SDSB, 2000–2011). But these policies did not have the same effect on the PCDD/F emission reduction in this paper.

Table 3 – Criteria for defining high-emission technology.

Sector	Criteria	Reference
Iron ore sintering	Scale of sintering machine: <90 m ²	NDRC (2011)
Electric arc furnace	Precipitator (head): non-bag filter	(MEP (2010); UNEP (2006))
Secondary non-ferrous metals production	Precipitator: non-bag filter	(MEP (2010); UNEP (2006))
Cu	No raw material pretreatment	(MEP (2010); UNEP (2006))
	Precipitator: non-bag filter	(MEP (2010); UNEP (2006))
	Production scale: <0.01 million ton/yr	NDRC (2011)
	No raw material pretreatment	(MEP (2010); UNEP (2006))
	Precipitator: non-bag filter	(MEP (2010); UNEP (2006))
	Production scale: <0.01 million ton/yr	NDRC (2011)
Al	No raw material pretreatment	(MEP (2010); UNEP (2006))
	Precipitator: non-bag filter	(MEP (2010); UNEP (2006))
	Production scale: <0.01 million ton/yr	NDRC (2011)
Pb	No raw material pretreatment	(MEP (2010); UNEP (2006))
	Precipitator: non-bag filter	(MEP (2010); UNEP (2006))
	Production scale: <0.01 million ton/yr	NDRC (2011)
Waste incineration	No raw material pretreatment	(MEP (2010); UNEP (2006))
	Precipitator: non-bag filter	(MEP (2010); UNEP (2006))
	Production scale: <0.03 million ton/yr	MEP (2010)*
	Precipitator: non-bag filter	(MEP (2010); UNEP (2006))
Municipal solid waste	Production scale: <300 ton/yr	MEP (2010)*
	Precipitator: non-bag filter	(MEP (2010); UNEP (2006))
	Precipitator: non-bag filter	(MEP (2010); UNEP (2006))
Medical and hazardous waste	Production scale: <300 ton/yr	MEP (2010)*
	Precipitator: non-bag filter	(MEP (2010); UNEP (2006))
Common industrial waste	Precipitator: non-bag filter	(MEP (2010); UNEP (2006))
	Precipitator: non-bag filter	(MEP (2010); UNEP (2006))

* Specific capacity value was not provided in MEP (2010), so the criteria of emission factor applied in this paper were taken as the reference.

In order to find out how the technology effect increased PCDD/F emissions, four key sectors with the most urgent control objectives were selected to analyze the technology changes in the years studied, i.e., waste incineration (WI), iron ore sintering (IS), electric arc furnace steelmaking (ES) and secondary non-ferrous metal production (SN) (MEP, 2010). The technologies, including production technology and pollution control technology, were categorized into low-emission technology (LT) and high-emission technology (HT). This classification is based on the national technology catalogue, technology policy, and literature analysis. Technologies that should be eliminated or restricted in use were defined as HT (Table 3), and the remaining technologies were categorized as LT. Hence, HT and LT are relative concepts, defined according to the relative magnitude on emission intensity. To avoid contradictions in technology definition between newer and older policies, the “high” or “low” label is based on the newest policy, catalogue and literature.

The production with HT and LT of four key industrial sectors are listed in Fig. 2. The total length of every bar represents the total production (or processed waste amount) of the sector. Although many policies were carried out to eliminate inefficient facilities, the outdated technologies with high PCDD/F emissions still took a large share in the total production from 2006 to 2010. It seemed that some inefficient facilities were shut down each year. Meanwhile, some facilities with outdated production were newly established. The sharp emission growth in the waste incineration sector from 2008 to 2010 and in the secondary non-ferrous metal production from 2006 to 2008 likely resulted from the increase of outdated production technology with high emission factors. From 2006 to 2008, processed waste, including municipal solid waste (MSW), medical and hazardous waste (MHW) and common industrial waste (CIW), increased by approximately 0.5 million tons, with a PCDD/F increase of 2.9 g I-TEQ. However, waste processing increased 0.9 million tons from 2008 to 2010, with a much higher PCDD/F increase of 53.8 g I-TEQ. The large difference in this increase of average emission intensity was caused by the increase of many incinerators without bag filters (0.43 million tons in 2006, 0.54 million tons in 2008, and 0.79 million tons in 2010). The growth of facility without bag filters also appeared in secondary non-ferrous metal production (including Cu, Al and Pb, 0.01 million tons in 2006, and 0.1 million tons in 2008), electric arc furnace steelmaking (from almost 0 tons in 2006 to 0.08 million tons in 2008) and iron ore sintering sectors (43.0 million tons in 2006, 59.8 million tons in 2008, and 77.5 million tons in 2010). This is a strong explanation for the technology effect being a PCDD/F emission-increasing factor.

The other reason to explain the emission-increasing role of the technology effect is that higher requirements for technology are needed in PCDD/F emission control, and the present improvement of the technology does not work effectively in the field of PCDD/F reduction. For example, for conventional pollutants, such as SO₂ and dust, common bag filters will have a great effect on emission reductions, but for PCDD/Fs more effective bag filters or even activated carbon injection technology are necessary.

The small-size sintering machine was recognized as the technology that should be eliminated or restricted in use

(NDRC, 2011). The decrease of small scales of the sintering machine (19.8 million tons in 2006, 19.7 million tons in 2008, and 14.9 million tons in 2010) presented the positive role of technology policies in PCDD/F emission control.

Generally, poor inefficient facilities are the main obstacle to PCDD/F emission reduction, and the weakness in implementing policies for restricting new industries with outdated facilities is a serious threat to PCDD/F control.

3.4. Policy instruments

According to the results above, policy suggestions were given as follows:

- (1) Since the composition effect played the most significant role in the PCDD/F emission change (contributed 43.4% in 2008 and 120.6% in 2010 based on 2006), Shandong administration should focus on industrial structure change in future work. The present industrial structure improvement, which is not efficient in PCDD/F emission reduction, should be adjusted to control the proportion of production capacities with high emission factors, such as iron ore sintering, steelmaking and secondary non-ferrous metal sectors.
- (2) The scale effect is in line with the total industrial production changes. As the source control measure, the excess capacity control policy will have a more remarkable effect in the PCDD/F emission reduction, if the policy in steelmaking and coke sector could be carried out the same as in the cement sector.
- (3) Further, strict steps should be taken to ban the installation or continuation of outdated facilities, such as the facilities without bag filters or electrostatic precipitators in the secondary non-ferrous metal and waste incineration sector. Industries without proper air control equipment are usually small-sized, and the small sized facilities and industries are always considered to be upgraded or eliminated. To reduce these industries, policy instruments that promote mergers and reorganization of enterprises are likely to be effective.
- (4) Advanced pollution control technology and alternative technology with less PCDD/F emissions should be applied according to the primary PCDD/F release routes, i.e., air, water, product and dust (see the emission factor in Table S2 in Supporting materials). For example, there is an over 80% PCDD/F release by residues in the waste incineration sector, and a nearly 100% PCDD/F release to air in the iron ore sintering and coke sector. Therefore, highly efficient air pollution control devices (APCD) are necessary for the waste incineration, cement, iron ore sintering, steelmaking, coke, foundries and secondary non-ferrous metal sectors. For the pulp and paper sector, the best available technology for PCDD/F elimination is reducing the application of elemental chlorine in the bleaching process.
- (5) Periodic monitoring of PCDD/F emission source is a direct way to verify the real emission reduction after the implementation of industrial policy or application of environmental technology. The local governments

Fig. 2 – Production of HT and LT in iron ore sintering sector (a), electric arc furnace steelmaking sector (b), secondary Cu (c), Al (d) and Pb (e) sector, and MSW, MHW and CIW sector (f) in 2006, 2008, and 2010, Shandong Province. HT: high-emission technology; LT: low-emission technology; MSW: municipal solid waste; MHW: medical and hazardous waste; CIW: common industrial waste.

should compel the companies, especially those who can afford the high cost, to monitor PCDD/F emissions on a regular basis. Moreover, the operation parameters of the APCD and production facilities are important to identify the PCDD/F formation and emission, which should be monitored frequently by the companies or using online monitoring facilities. With the accumulation of these data, which cover different scales and technologies of industries, the efficiency of policy and technology applications could be evaluated.

- (6) Shandong Province has been selected by the State Council as a pilot province of iron and steel industrial structure adjustment since 2011, and the government has issued several policies on task assignment, company annexation and reorganization, as well as financial support (GSD, 2012). This provides a good chance for Shandong to integrate the control of PCDD/Fs into the national industrial structure adjustment policy in the iron and steel sector, which can also deliver lessons for other sectors. Only when the production of sectors with high emission

factors declines substantially, will PCDD/F emissions be reduced.

3.5. Uncertainty analysis

A comprehensive and systematic field monitoring work is necessary for estimating PCDD/Fs accurately at the provincial level. All kinds of PCDD/F emitting facilities with different material, technological process and pollution control equipment should be considered. Unfortunately, obtaining such suitable emission factors for Shandong Province is not feasible at present. Therefore, uncertainty may be brought to the PCDD/F emission estimation by adopting the national average emission factors in this paper in spite of applying the latest revised edition. Moreover, at the initial stage of accumulating PCDD/F data, the inconsistent statistical standards of national POP survey before and after 2010 in the iron ore sintering and coke sector also added the uncertainty, which could be improved by accomplishing the PCDD/F inventory and implementing the system of statistical reports on POPs in the future.

4. Conclusions

In summary, the total PCDD/F emissions in Shandong presented a significant increase from 2006 (401.9 g I-TEQ) to 2008 (614.1 g I-TEQ) and a slight decrease from 2008 to 2010 (601.8 g I-TEQ). According to the decomposition analysis results, the largest influencing factor for PCDD/F emission changes was the composition effect (contributed 43.4% in 2008, and 120.6% in 2010 based on 2006), which was also an emission-increasing factor. In order to reduce PCDD/F emissions, the prior controlled sectors in the process of industrial structure adjustment are the iron ore sintering, steelmaking and secondary non-ferrous metal sectors. Facilities without bag filters or electrostatic precipitators in secondary non-ferrous metal and waste incineration sectors should be strictly banned to install and produce. The policy instruments for promoting mergers and reorganization of enterprises will be effective in the upgrade or elimination of small-sized facilities and industries.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <http://dx.doi.org/10.1016/j.jes.2014.05.018>.

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