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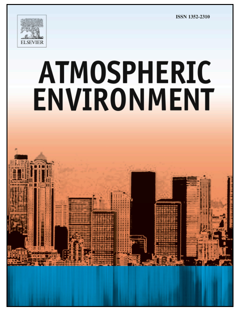

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A Review of Receptor Modelling of Industrially Emitted Particulate Matter

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Highlights:

Industrial processes have been identified as an important source of airborne PM.

PM from different sites within the same industry may vary appreciably in composition.

PM from different processes within the same industrial site can differ substantially.

Local source profile measurements are needed for industrial PM source apportionment.

ABSTRACT

This review summarises the different receptor models that have been adopted at industrial and urban sites to apportion the sources of particulate matter (PM) from industries. Industrial processes and those associated with industry (such as transportation) are an important source of airborne PM which includes trace elements, organic and elemental carbon, and PAHs. Industry also emits gaseous pollutants which form secondary aerosol in the atmosphere. Most published studies have employed chemical mass balance (CMB), positive matrix factorization (PMF) and/or principal component analysis (PCA) models as source apportionment tools. These receptor models were mostly applied to fine particulate matter ($PM_{2.5}$) and PM_{10} compositional data, particularly the inorganic constituents. Some studies have combined two or more of these receptor models, which provides useful information on the uncertainties associated with different models. Industry has been reported to contribute from 0 to 70% of PM mass at industrial sites. It appears that some studies are unsuccessful in apportioning PM from industry, e.g., unable to distinguish industrial emissions from other sources. A critical evaluation of the literature data also showed that the choice of appropriate tracers for industry, both generically and for specific industries, varies between different PM source apportionment studies. This is not surprising considering the significant difference in source profiles of PM from different types of industry, which may compromise source apportionment of industrial emissions using CMB with non-local source profiles. It may also affect the attribution of industrial emissions in multivariate statistical models (e.g. PMF and PCA). It is concluded that a general classification of the source “industry” is rarely appropriate for PM source apportionment. Indeed, such studies may even need to consider the different processes within a particular industry, such as a steelworks, which emit PM with significantly different chemical signatures. It is suggested that future source apportionment studies should make every effort to measure source profiles of PM from different industrial processes, and where possible, use multiple models in order to more accurately apportion the source emissions from industry.

Keywords: Source apportionment; industrial emissions; receptor modelling; metals; particulate matter; steel industry

1. INTRODUCTION

Airborne particulate matter (PM) is a complex pollutant emitted directly from anthropogenic and natural activities (Poschl, 2005) or formed indirectly as secondary aerosol (Harrison and Yin, 2000). Particulate pollutants are composed of a complex mixture of substances with diverse physical, chemical and biological composition. A number of health problems have been associated with exposure to PM. For example, epidemiological studies have found strong correlations between concentrations of PM and hospital admissions and mortality due to respiratory and cardiovascular diseases (Pope and Dockery, 2006).

Rapid economic and industrial developments have led to increased energy consumption, emissions of air pollutants and poor air quality in major cities of the world, especially in developing countries (Chan and Yao, 2008). Hence, there is a compelling need for quantification, identification and apportionment of these pollutants in order to facilitate their reduction through proper management plans. Emission inventories and chemistry-transport models are important tools in the evaluation of particulate matter pollution. However, these models have some limitations, e.g., due to the fact that important sources of PM are fugitive and hence often poorly quantified (Almeida et al., 2005). Additionally, gas-to-particle transformation models are not always able to describe adequately the contribution from secondary aerosol. Therefore, receptor modelling remains an important tool. Receptor modelling uses physical and chemical characteristics of air pollutants to identify and apportion their contributing sources. The two generic method types of receptor models are the Chemical Mass Balance (CMB) model (Watson et al., 2002) and factor analytical methods (Hopke, 2003). The latter includes Principal Component Analysis-Absolute Principal Component Scores (PCA-APCS) (Thurston and Spengler, 1985; Garcia et al., 2006), Positive Matrix Factorization (PMF) (Paatero and Tapper, 1994) and UNMIX (Henry, 1997, 2002).

Application of receptor models for source apportionment of PM has been well established in published pollution studies (Viana et al., 2008a; Yatkin and Bayram, 2008; Mansha et al., 2012;

Belis et al., 2013, 2014; Pant and Harrison, 2012; Pant and Harrison, 2013). Industry has frequently been reported to be one of the important sources of airborne PM, alongside other sources such as traffic, crustal material, secondary aerosol, sea spray, incineration, fuel oil burning, biomass burning, and coal combustion (Harrison et al., 2003; Marcazzan et al., 2003; Qin and Oduyemi, 2003; Chio et al., 2004; Karar and Gupta, 2007; Pant and Harrison, 2012), particularly in industrial cities (Oravisjarvi et al., 2003; Querol et al., 2007; Tsai et al., 2007; Alleman et al., 2010). In EU member states, industrial processes are the second and third largest source of primary $PM_{2.5}$ and PM_{10} respectively (http://www.eea.europa.eu/data-and-maps/figures/sector-contributions-of-emissions-of-2). The objective of this review is to examine critically the application of various receptor models used for source apportionment of particulate matter from industry. It will first give an overview of the emitted PM pollutants from industries and particularly the iron and steel industries. It will then review the receptor modelling of PM from industries. Finally it will compare the PMF profiles used in the literature with the USEPA SPECIATE database for different processes for iron and steel-making in order to evaluate the results from current receptor modelling on industrial pollutants from this source.

2. INDUSTRIAL EMISSIONS OF PARTICULATE MATTER POLLUTANTS

In this section, the major types of PM-related pollutants will be briefly introduced. It will also include a specific exemplar industry, iron and steel manufacturing, which has been the subject of several studies.

2.1 Major Particulate Phase Pollutants from Industries

There are many types of industry. Major primary industries that contribute to PM emissions include but are not limited to: manufacturing (including automotive, steel and metal-making industries), aerospace, agriculture, chemical, construction, energy. Particulate phase pollutants from industries include metals (Querol et al., 2007; Cetin et al., 2007), OC/EC (organic carbon, elemental carbon), PAHs (Rehwagen et al., 2005; Jang et al, 2013), and water soluble ions (Querol et al., 2002).

2.1.1 Trace metals

Trace metals are one of the most characteristic chemical species associated with PM emission from many industries and are the major tracers used in many receptor modelling studies. Trace elements in industrial PM emission are related to the handling and processing of raw materials, handling of intermediate products and production of end products.

EEA (2012) reported that industrial processes make a significant contribution to the total EU-27 emissions of heavy metals (36% Pb, 25% Cd, and 41% Hg), despite significant reductions since 1990. In Canada, industrial processes account for 72%, 79% and 32% of total emissions of Pb, Cd and Hg (http://www.ec.gc.ca/inrp-npri/default.asp?lang=En&n=0EC58C98-1). Metal production is one of the major industrial processes contributing the emissions of total trace elements such as Cd, Cr, Cu, Hg, Ni, Se, V, and Zn in the UK in 2009 (Table 1). A study by Querol et al. (2007) also showed a number of trace elements in airborne PM are associated with industrial emissions in Spain.

Analysis of airborne PM close to steel plants has shown that Fe, Mn, Zn, Pb, Cd and K are associated with emissions from the steel and iron plants. Microscopic analysis of individual particles has confirmed the presence of individual Fe-rich particles close to steel plants. For example, Moreno et al. (2004) identified iron spherules in both fine and coarse PM fractions at a steelworks in Port Talbot, South Wales, UK; Ebert et al. (2012) observed a significant fraction of individual iron oxides and iron mixtures in airborne PM near a steel industry in Duisburg, Rhine-Ruhr area, Germany. Elevated concentrations of some elements at the steel industry sites derive from the raw materials being used for steel production. For example, raw materials including iron ores (FeO, Fe_2O_3, Fe_3O_4), limestone ($CaCO_3$) and dolomite ($CaMg(CO_3)_2$) are used in a blast furnace (BF) while lime (CaO) and fluorspar (CaF_2) are used in a Basic Oxygen Steel plant (Machemer, 2004). Integrated steel plants are also known for high emissions of mercury (Pacyna and Pacyna, 2002; Themelis and Gregory, 2002; Borderieux et al., 2004). Asia and Europe are the regions where steel industries contribute most to the global mercury budget (Pirrone et al., 2001; Pacyna et al., 2006). Mukherjee et al. (2008) reported that annual mercury emissions from iron and steel industries in India increased by 25% between 2000 and 2004.

2.1.2 Organic/elemental carbon (OC/EC)

Carbonaceous particles comprising OC and EC are another pollutant generated from industrial emissions. Some of the OC/EC are directly emitted from particular industrial processes and some are associated with relevant activities of industries (see Section 2.3). Globally, industries contribute about 10% and 15% of OC and BC (black carbon) emissions respectively (Bond et al., 2004). In early 21st century China, industrial BC emissions arise primarily from uncontrolled coal-fired stokers and from the production and use of coke in the iron and steel industry; total coal-derived emissions are 83 Gg (85% of the industrial sector total of 97 Gg) (Streets et al., 2001).

Tsai et al. (2007) measured elevated concentrations of OC and EC at the cold forming unit of an integrated steelworks in southern Taiwan. Highly time-resolved ambient measurements made at a fence-line site adjacent to a large coke production plant in the USA also revealed high concentrations of OC (40% of total measured $PM_{2.5}$) and EC (25% of measured $PM_{2.5}$) (Weitkamp et al., 2005).

Polycyclic Aromatic Hydrocarbons (PAHs) are a group of organic compounds that are mainly produced by incomplete combustion and pyrolysis of organic material (Manahan, 2009). Industrial processes are a minor source (5%) of PAHs in the UK in 2008 (AEA, 2010) and contributes 9% of PAHs in the EU in 2011 (EEA, 2012). The most important industrial sources of PAHs include primary aluminium and coke production (e.g. as part of iron and steel production), waste incineration, cement manufacture, petrochemical industries, creosote and wood preservation, bitumen and asphalt industries, rubber tyre manufacturing, and commercial heat/power production (European Commission, 2001) and paper mills (Fauser et al., 2011). The PAH emission factors are affected by incoming fuel, the manufacturing process, and the air pollution control devices (Ravindra et al., 2008). The significantly higher PAH levels at an industrial site than at control site and the La Plata city centre in Argentina also suggest that the refinery and petrochemical plants are important sources of PAHs (Rehwagen et al., 2005).

2.1.3 Water soluble ions

Water soluble ions have been observed at significant concentrations in industrial sites (Kumar et al., 2001; Oravisjarvi et al., 2003; Samara et al., 2003; Karar and Gupta, 2007; Gildermeister et al., 2007; Viana et al., 2008b; Amato et al., 2009; Zeng et al., 2010; Pancras et al., 2013). K and Cl have been suggested to be associated with sinter plant emissions (Dall'Osto et al., 2008; Hleis et al., 2013).

2.2 PM Pollutants from Different Processes within a Particular Industry: Steel manufacturing as an example

A modern integrated plant is usually a complex operation, with more than one industrial process unit. For example, steel manufacture involves coke production, sintering, blast furnaces and basic oxygen furnace steelmaking (BOF). Sintering involves mixing iron ores, filter dusts and mill scale all fused together as appropriate feedstock for the BF (Brigden et al., 2000), while in coking processes, pulverized bituminous coal is used as fuel in order to reduce iron oxides and remove volatile impurities (http://ecm.ncms.org/ERI/new/IRRironsteel.htm). The BF is a high temperature driven process where metallic iron reduction from the oxide form takes place by burning with coke produced in the coking process. The steelmaking section involves addition of various alloying elements to give the finished materials the combination of properties desired. This takes place in three ways, i.e. the BOF for processing pig iron and the electric arc furnace (EAF)-for recycled materials and the open hearth furnace (OHF) where excess carbon and other impurities are burnt out of the pig iron to produce steel. Presently, about 70% of the world steel is produced from BOF while 29% comes from EAF (http://www.worldcoal.org/coal/uses-of-coal/coal-steel/).

Each unit may emit PM with specific characteristics. Figure 1 shows the source profiles of PM from two industrial processes in a steel plant and charcoal manufacturing from the USEPA SPECIATE database. There are significant differences in the emission profiles. For example, BOF with an electrostatic precipitator produces high concentrations of sulphate and Si, whereas BOF without control emits high concentrations of Fe and Mn but lower concentrations of sulphate and Si; a sinter plant generates high emissions of Fe, Pb, K and Cl, whereas charcoal manufacturing (not necessarily for a steel plant) has a high concentration of Al, Ca, and Se (Figure 1). A recent study by Tsai et al. (2007) also suggested that K and Pb, which contribute a significant percentage (15 and 2 %) to the total observed particle mass, are associated with the sintering process. Similarly, Oravisjarvi et al. (2003) found that the sinter plant contributes 96% and 95% of the total measured concentrations of Pb and Cd in PM at Rahee, Finland. The study of Machemer (2004) showed elevated concentration of Fe, Al, Si, S and Zn at sections close to both BOF and blast furnaces (BF). At the coke making process, major elements observed by Tsai et al. (2007) were S, Fe and Na. In the cold forming aspect of the iron and steel industry, major elements observed in the particles were S, Fe, Na, K and Ni. The hot forming process showed a high abundance of S, Fe, Na and Ca (Tsai et al., 2007). These reports highlight the importance of using local profiles for CMB type models, and provide useful references for identifying tracers for factor analysis-based models. More detailed discussion on these aspects will be given later.

2.3 PM Pollutants from Industrially Related Activities

When considering PM emission from a particular industry, one should also consider the other processes that are associated with that industry, for example, transportation of raw materials and end products and energy consumption. This leads to primary emission of combustion aerosols, including vehicular emission,s as well as re-suspended dust. Based on emission reports by EU countries under the CLRTAP and NEC Directive, EEA (2012) estimated that 36%, 25%, and 41% of the Pb, Cd and Hg in the EU is emitted from energy use in industry. It is however challenging to apportion the emissions from energy use in industry relative to non-industrial sources. It is also difficult to distinguish the re-suspended dust from the industry itself and those from other processes such as wind-blown dust and the dust generated from working agricultural land. Dust resuspension from raw material transportation is especially relevant in the case of the ceramic industry.

Apart from the primary particulate pollutants discussed above, industries are also known for emission of gaseous pollutants such as carbon monoxide (CO), sulphur dioxide (SO_2), nitrogen oxides (NO_x) and hydrogen gas (H_2), and volatile organic carbon (Ogulei et al., 2006; Ogulei et al., 2007; Tsai et al., 2008; Johansson and Söderström, 2011; Pancras et al., 2013). Some of these gaseous pollutants can be transformed into secondary compounds which are commonly detected in urban aerosols. It is very challenging for receptor modelling to estimate how much of the secondary aerosols are from the primary pollutants emitted from different industries.

3. RECEPTOR MODELLING OF PM FROM INDUSTRIAL EMISSIONS

3.1. Industrial Sites

Table 2 summarizes different methods of receptor modelling applied to ambient PM measurements at industrial sites all over the world. The types of industries where receptor monitoring sites were located include steelworks, metallurgical plants, oil refineries, petrochemical works and small factories. Most of the studies collected PM_{10} or $PM_{2.5}$ samples, with a few also collecting data on total suspended particles (TSP) or $PM_{2.5-10}$. Trace metal concentrations were often used as the source data for receptor modelling (Table 2). OC/EC and ionic components were also included in combination with the metals in some studies. A few of the studies included PAHs as source data. Several types of models have been used including PCA, PCFA (Principal Component/Factor Analysis), CMB, Nested CMB, PMF or Multilinear Engine-2 (ME-2).

Elevated PM mass concentrations have been observed at some industrial sites compared to residential stations. For example, Xue et al. (2010) reported that the annual PM_{10} concentrations ranged from 131 to 179 µg m^{-3} at industrial sites compared to 86 µg m^{-3} at a rural background site in Panzhihua, China. Kim and Jo (2006) showed that the average PM_{10} mass levels was 81 and 71 µg m^{-3} during winter and summer at an industrial site in Pohang, Korea compared to 52 and 42 µg m^{-3} observed at a residential site. Yatkin and Bayram (2008) found that PM_{10} mass levels were 80 µg m^{-3} at an industrial site, which is about twice that of a suburban site in Izmir, Turkey. Querol et al. (2006) reported that the PM_{10} mass level at an industrial site (Changqian, China) was 197 µg m^{-3}, which was 41 µg m^{-3} higher than that at an urban site (Hankou, China). An extremely high PM_{10} concentration, 305 µg m^{-3}, was also reported at an industrial site in China (Zeng et al., 2010). It is apparent that many of these studies conducted at both industrial and residential/background/urban sites report mass levels of PM_{10} greater than the European Union 24-hour mean Limit Value of 50 µg m^{-3}.

The sources (factors) identified in different studies include industry, fuel/oil/coal combustion, traffic (including exhaust and non-exhaust emissions), crustal (soil/dust/minerals), secondary, marine and waste incineration. Literature reports have identified many different types of sources, some of which are similar but with different terminology (e.g., Kim and Jo, 2006; Querol et al., 2006; Ogulei et al., 2006; Viana et al., 2008; Lim et al., 2010). To simplify the comparisons, we also combined some of the sources together to report in Tables 2 and 3. The details of such combinations are shown in the footnotes of Tables 2 and 3. If one or more sources are not classified into one of the categories in Tables 2 and 3, they are listed as “others”. “Others” also include mixed sources such as metallurgy/fossil fuel combustion and waste incineration/marine aerosol by Kim and Jo (2006), steel and fuels by Yatkin and Bayram (2008), incineration and Pb-related industry by Lim et al. (2010), and regional and marine by Viana et al. (2008b); vehicle and industrial oil burning by Lodhi et al. (2009).

In some cases, up to 48% of the source contributions were not identified, suggesting that the model resolution was not good enough. This could be due to inadequate data (e.g. insufficient samples, poor quality analytical data or inappropriate sets of analytes) causing a failure of the modelling.

A few studies have adopted two or more receptor modelling approaches for source apportionment. Some of them produced similar results from different models, such as Viana et al. (2008) and Callen et al. (2009). However, source contributions estimated in some studies (e.g., Yatkin and Bayram, 2008; Srivastava and Jain, 2008) are significantly different using different models. In the latter cases, it is possible that one of the models or both failed to produce satisfactory resolution and/or that the datasets are insufficient to resolve the sources. For application of the multivariate statistical models (PCA, PMF) it is strongly advisable for the ratio of the number of independent samples to the number of species entered in the model to exceed three (Thurston and Spengler, 1985), but this guideline is not observed in all cases, leading potentially to model instability.

The reported contribution of industry to the PM mass is highly variable. Most studies have apportioned less than 10% of PM to industrial sources (Table 2). A very low industrial contribution of 1% has been reported (Ogulei et al., 2006; Gupta et al., 2007). In one case, no contribution from industry was identified at an industrial site (Samara et al, 2003). In Hammond et al. (2008), iron–steel manufacturing/waste incineration together contributed 0.1 and 4% to $PM_{2.5}$ at East and Southwest Detroit, respectively. In Callen et al. (2009), industry and traffic sources were identified as a single factor. In these studies, the specific contribution from industry cannot be ascertained. It is clear that in some studies, the contribution of PM from “industry” is beyond the resolution capabilities of the RMs used (contributions of 1-2% or less). In Lodhi et al. (2009), the contribution to $PM_{2.5}$ from the steel industry was resolved to be 8% but the full contribution from industries must be more than 8% because another mixed source include industrial emissions. Several studies have apportioned more than 10% of PM to industry (Alleman et al., 2010; Viana et al., 2008b; Chung et al., 2006; Yatkin and Bayram, 2008; Karar and Gupta, 2007; Oravisjarvi et al., 2003). The highest contribution from industry to ambient PM reviewed in this study was estimated to be 70% by Cetin et al. (2007).

There are many reasons for the large difference in the apportioned contributions of PM from industry including: (i) distance of the industrial units to the sampling sites; (ii) meteorological conditions (e.g. whether the site is downwind or upwind); (iii) particulate emission control measures in place in most industrial plants. Another potentially crucial reason is the choice of industrial tracers in the receptor models in these studies. Multiple emission sources of certain marker elements could create conflicts during apportionment exercises. This will be discussed in more detail in the next section.

The contribution of combustion sources, encompassing stationary burning of oil, fuel, wood or coal, to the total PM ranges from 0.4 to 58% (Table 2). Combustion is reported to be a major source (>20%) of PM in some of the studies (e.g. Xue et al., 2010; Karar and Gupta, 2007; Querol et al., 2006; Mazzei et al., 2008; Chung et al., 2006; Samara et al., 2003; Castanho and Artaxo, 2001). Nested CMB applied for source apportionment of PM_{10} by Xue et al. (2010) at industrial sites in China indicated coal combustion ash to represent the largest source of PM_{10} (26%). However, it needs to be emphasized that the influence of combustion sources on ambient PM may or may not be directly related to industry. No contribution from combustion was identified in a few studies (Oravisjarvi et al., 2003; Cetin et al., 2007; Viana et al., 2008b; Yatkin and Bayram, 2008; Alleman et al., 2010). This could be due to an insignificant contribution from the combustion sources but model bias or incapability of the models to identify the source could not be ruled out. Jang et al (2013) found a similarity in the PAH congener profiles of coal combustion and steel industry emissions, which was resolved only by inclusion of a large number of congeners.

The traffic source is often a major source of PM even at the industrial sites. It is typical of industrial areas to have high traffic flows due to transportation of raw and processed goods as well as personnel mobility. Heavy-duty vehicles, known large emitters of particles (Charron and Harrison, 2005), are often used for transportation of raw materials and processed goods in industry. This is in addition to the contribution from vehicular emissions not associated with the industry and long-range transported sources at those sites.

Particles with a crustal signature comprised of soil and road dusts as well as cement dust are another important source of PM at industrial sites. Most studies listed in Table 2 have attributed an appreciable proportion of PM, especially in $PM_{2.5-10}$, PM_{10} and TSP fractions, to crustal matter. Re-suspended dusts from roads and all forms of construction works, and windblown soil at the industrial sites are probable contributors. Vehicular movements at the industrial sites could increase dust particles through resuspension processes (Charron and Harrison, 2005). However, it is difficult to apportion the crustal matter from industry due to the overlapping signatures of the possible contributing sources.

3.2 Urban/Residential Sites

As stated above, PM mass concentrations in a number of selected studies in residential areas were generally lower compared to the values reported at the industrial sites. Table 3 compiles selected source apportionment studies carried out in urban/residential areas. Despite the fact that studies presented in Table 3 were conducted around the perimeter of residential/urban areas sites, an industrial factor was still prominent in some of the receptor modelling studies. The percentage contributions assigned to industry range between 2 and 37%. Elevated percentages assigned to the industrial source in the residential areas might be related to prevailing meteorological conditions (wind direction) during sampling, and the source to receptor site distances maximising the impact through local dispersion processes (e.g. from an elevated point source) (Almeida et al., 2005; Yatkin and Bayram, 2008).

Table 3 also shows that some studies were unable to differentiate between industry and traffic by the receptor models used and therefore reported them as a single source (Almeida et al., 2005; Callen et al., 2009). Coal combustion is another significant source of PM pollution in the residential areas, especially in studies from India and China (Chowdhury et al., 2007; Xue et al., 2010). This may arise partly from industrial processes.

4. PM MARKER ELEMENTS FOR SOURCE APPORTIONMENT OF INDUSTRIAL EMISSIONS

The choice of marker elements for industrial factors/sources in source apportionment is a crucial aspect of receptor modelling. In source apportionment studies, different authors have chosen different marker elements for "industry" (as a general term), for example: As, Zn, Pb, Cs, Tl, Zr, Hf, Ce and Cu (Almeida et al., 2005; Viana et al., 2008b); Pb, Co, Ce, Cr (Hien et al., 2001); Zn, Pb, Si, Ni, Mn, Fe, S (Castanho and Artaxo, 2001); Cd, Pb, Cr, Ni (Heal et al., 2005); Zn and Pb (Zn and Pb smelters, Connell et al., 2006; Kim et al., 2007; Mazzei et al., 2008). It needs to be emphasized that "industry" here refers to a general term rather than a specific industry. A more comprehensive list of marker elements attributed to industrial sources is shown in Tables 2 and 3.

A range of marker elements have been used for the steel industry. For example, in the study of Xue et al. (2010) at a mixed industrial location with iron and steel industries, Ti, Cr and Mn were used as markers for metallurgical industry. Tsai et al. (2007) and Oravisjarvis et al. (2003) used K, Pb, Fe, Ca, S/SO_2 and Na as tracers for steel production. In the work of Cetin et al. (2007), Zn, Fe, Pb, Mn and Cd were used as steel industry fingerprints. The study by Hammond et al. (2008) adopted Zn, Fe, Mn, K and Pb as steel emission tracers, some of which are also used by other authors.

There are several major issues arising from the above discussion on the choice of tracer elements for industries. The first issue is how "industry" is defined. "Industry" is in general referred to as one category of emission sources which encompasses a wide range of plants. It is clear that "industry" in one study is not necessarily the same as that in another study. In some cases, there is only one dominant industry that may affect the PM in a particular area. This should to some extent facilitate the choice of tracer elements for receptor modelling. However, frequently, there is more than one industry in a particular area. Since each industry may emit PM with sharp differences in source profiles, using a single set of tracer elements to distinguish the source contribution from "industry" as a whole can be problematic.

The second issue is related to different emission source profiles from industrial processes in a particular industrial unit. Marker elements for industries depend on the nature of different processes and activities taking place within the industry (Querol et al., 2007). As shown in Figure 1, different processes at a steel and iron plant can have significant differences in their source profiles. Therefore, using a single set of elements as tracers for a particular industry as a whole can sometimes be problematic as well.

The third issue is the presence of abatement plant for a particular industrial process in a particular industrial unit. For example, the source profiles of BOF with an electric precipitator are significantly different to those without control (Figure 1). This may to some extent support the choice of different tracer elements for a particular industrial process in different studies but this choice needs to be justified by actual source profile measurements.

The fourth issue of concern is that the multiple sources of some elements that have been used as marker elements may lead to wrong attribution of a source. For example, K is emitted from burning wood or other biomass, vehicular sources, sinter plants and incinerators (Hays et al., 2005; Lim et al., 2010; Hleis et al. 2013). Fe is a component of crustal matter and Fe, Cu, Zn, and Ba are associated with non-exhaust emissions from road traffic (Thorpe and Harrison, 2008; Pant and Harrison, 2013). OC/EC are emitted from many sources including road traffic. Calculation of enrichment factors (EF) can be useful to differentiate natural and anthropogenic emissions (Kothai et al., 2011). The ratios of some specific elements may also be employed to differentiate steelworks emissions from either traffic or other anthropogenic sources. Connell et al. (2006) used the Mn/Zn ratio to identify steelworks emissions in $PM_{2.5}$ sampled at Steubenville, OH, USA. Cl and S are sometimes used as tracers for industries (Prati et al., 2000; Chung et al., 2006) but there are obviously many other potential sources for these elements. It is therefore difficult to resolve the emission sources of elements such as K, Cl, S and Fe in receptor modelling except by inclusion of other tracers. A typical example is the use of levoglucosan along with K as tracers for biomass burning (Zhang et al., 2010; Harrison et al., 2012).

The summary in Tables 2 and 3 shows a wide range of tracer elements for "industries". This to some extent is justifiable because different industries have different chemical signatures (tracers). Many previous receptor modelling studies appear to over-simplify the source apportionment of industrially emitted PM. There is a tendency in some studies using PMF or PCA methods to associate factors containing trace metal signatures with "industry" without supporting information on industrial emission profiles. We recommend that the choices of tracers for industries should be supported and justified by comprehensive source profiles from major industries in the area of interest.

In the following, we will quantitatively compare the profiles of PMF factors used for source apportionment of PM from steel production processes with those of the USEPA SPECIATE source profile. Our intention is to further examine the appropriateness of the choice of tracer elements for different processes associated with steel industry activities.

5. PMF FACTORS VERSUS USEPA SPECIATE PROFILES FOR STEEL PRODUCTION PROCESSES

Here, we compare the factor profiles identified by PMF with USEPA SPECIATE source profiles from general steel production processes, sintering and coking processes and a blast furnace (Figures 2a-2d). We have chosen these processes mainly because of the data availability (both the USEPA source profiles and the PMF factors). Only a few PMF studies have identified the steel industry and/or process units related to the steel industry as a source. Some studies have identified a steel industry factor but this was mixed with another source such as waste incinerator. In this latter case, the factor was not included in the comparison in Figure 2. It should be emphasised that these PMF factors are different from ambient concentrations of PM components and represent the fractional composition of the factor attributed to the specific source.

Figure 2a shows that there are some differences in the PMF profiles of steel production with general iron production source profiles in the USEPA SPECIATE database, but most of the elements and in particular the tracer elements, including Fe, Zn and Mn, fall within the 1:10 and 10:1 lines. Some elements such as Ni, Cr, Cu and sometimes K are outside of the 10:1 lines. This may be linked to their use in specific processes not represented in either the PMF or SPECIATE profiles. The level of information associated with each dataset is insufficient to make a specific judgement.

Figure 2b shows that the Fe content in the PMF profile of the sinter plant factor from Alleman et al. (2010) is similar to that in USEPA SPECIATE database. However, most of the other elements are outside of the 1:10 line. In terms of coking, there seem to be large discrepancies between the Alleman et al. (2010) PMF factor profile with that in the USEPA SPECIATE database (Figure 2c). This may result from differences in the trace element composition of feedstocks for the respective plants that were sampled. The PMF blast furnace factor (Steel 1) profile from Taiwo et al. (2014) agrees very well with the USEPA SPECIATE profiles from the blast furnace process (Figure 2d). Fe, K, Mn, and Zn are close to the 1:1 line, while Ni and Cu were outside of the 1:10 line and Cr was not identified in the PMF factor.

In the USEPA SPECIATE/PMF scatter plot shown in Figure 2(a-d), good agreement was observed for some marker elements adopted in different studies, suggesting that the choice of relevant factors was appropriate. However, some discrepancies were also observed for tracers related to steelworks processes. This may be caused by several factors.

One reason may be differing materials inflow at the steelworks processing units reported in the USEPA SPECIATE database and the published work, which may result in a dissimilar chemical profile of PM emissions from each process from plant to plant. Unfortunately, there are limited source profile data available in the literature to evaluate this possibility. The relationship of the source profile measured directly upon emissions from the sintering process from Tsai et al. (2007) against USEPA SPECIATE data is shown in Figure 3. Most elements are within 1:10 and 10:1 lines except for Cu and Ba, which gives some confidence in the comparison of source profiles from different studies. However, there are clear differences for many of the elements.

A second reason may be related to pollution control systems in place at some steelworks. On the issue of pollution control systems, the USEPA SPECIATE data showed that there are significant differences in source profiles of PM from BOF with and without an electrostatic precipitator (Figure 1). Information on the pollution control system at the steelworks foundry, sintering and EAF are not revealed in the USEPA SPECIATE database. However, no control system was in place at the coking plant represented in the USEPA SPECIATE data.

These above discussions indicate that even with the PMF receptor modelling, it is preferable to obtain the source profiles from on-plant measurements to support the choice of factors and tracer elements.

7. CONCLUSIONS AND RECOMMENDATIONS

Industrial emissions are an important source of particulate substances including metals, carbonaceous species and PAHs in the atmospheric environment. Receptor models such as CMB, PMF and PCA have been used to quantify the contribution of industrial emissions to ambient PM. A few studies have combined two or more models which makes it possible to compare the performance of each model. Receptor modelling at industrial sites has assigned between 0 and 71% of PM to industrial emissions. This assignment does not generally include the likely contribution of industrially-related activities such as combustion and transportation of materials. A comprehensive evaluation of different receptor modelling studies at industrial sites demonstrated that many different elemental profiles have been attributed to industry, often without any check against known source profiles for local industrial processes. This makes it difficult to evaluate the results from these source apportionment studies, in particular when more complete information including the control technologies at the plants and the source profiles of PM from the industries around the receptor sites is not available.

We suggest that in future receptor modelling of industrially emitted PM:

(1) Where possible, multiple receptor modelling techniques are used in order to provide a means to evaluate the uncertainties.

(2) Receptor modelling at paired sites, one close to an industrial site and a background site, are conducted to allow a quantitative evaluation of the impact of a particular industrial plant.

(3) Local source profiles of PM from different industries which may contribute to the receptor site are measured to support the assignment of source profiles in non-CMB type modelling techniques.

(4) More source profiles associated with different industrial processes in different industries should be measured to enhance the data available for use in CMB models and to assist source attribution in PCA, PMF and related models.

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TABLE LEGENDS

Table 1: Contribution of each trace metal from industrial processes to total emissions and their major sources in the UK based on 2009 United Kingdom National Atmospheric Emissions Inventory.

Table 2: Results of Source Apportionment (SA) with different receptor models at industrial sites.

Table 3: Source Apportionment with different receptor models at residential sites (selected studies) with a reported industrial contribution.

FIGURE LEGENDS

Figure 1: Source profiles of charcoal manufacturing, sinter plant and BOF plant (with electrostatic precipitator). From US EPA SPECIATE database.

Figure 2: Scatter plots of PMF factor profiles (in percentage) from published studies versus USEPA SPECIATE source profiles for (a) general steel production, (b) sinter plant, (c) coke plant and (d) and blast furnace. In Fig. 2a, Gildemeister et al. (2007) (1): site 1-Allen Park site; Gildemeister et al. (2007) (2): Dearborn site at Detroit industrial area, USA; PMF profile in Taiwo et al. (2014) (Fig. 2a) was a mixed factor comprising Steel 2 (BOS) and Steel 4 (sinter plant); PMF factor profiles in Gildemeister et al. (2007) were kindly provided by the authors; PMF profiles of iron/steel factor from Pancras et al. (2013) were estimated (so carries small subjective error) from concentration of each element (in ng m^{-3}) in Fig. 3 in the original paper and the apportioned iron/steel factor concentration of 0.36 µg m^{-3} (Table 4 of the original paper). PMF factor profiles of sinter plant (Fig. 2b) and coke dust (Fig. 2c) are from Alleman et al., (2010) and that of blast furnace is from Taiwo et al. (2014). The USEPA SPECIATE blast furnace profile: PM (0-38 µm) from kish graphite from blast furnace process in iron and steel manufacturing. Ni and Ba made negligible contribution to factor Steel 2 and 4 in Taiwo et al. (2014) so were not included in comparison (Fig. 2a); similarly Cr made negligible contribution to factor Steel 1 in Taiwo et al. (2014) so was not included in comparison (Fig. 2d). Please note that some elements were reported in USEPA SPECIATE source profiles but not in PMF factor profiles; and vice versa. In those cases, the data could not be shown in the figures.

Figure 3: Regression plots of USEPA SPECIATE vs Tsai et al. (2007) source profiles for the sintering process in the steel industry.

Table 1: Contribution of each trace metal from industrial processes to total emissions and their major sources in the UK based on 2009 United Kingdom National Atmospheric Emissions Inventory.

	Total Emissions (tonnes)	Industrial contribution %	Major sources
As	13	93	Treated wood for industrial combustion; metal production; public electricity and heat production
Cd	2	78	Non-ferrous metal production and iron and steel manufacture (as well as other forms of industrial combustion), energy production (include a significant proportion from waste combustion and fuel oil combustion for electricity generation)
Cr	26	89	Coal combustion, iron and steel production in integrated works and in electric arc furnaces and the production of chromium based chemicals
Cu	52	49	Metal production, combustion of lubricants in industry and coal combustion
Pb	60	87	Metal production and combustion of lubricants in industry
Hg	7	99	Iron and steel production processes, public electricity and heat production, waste incineration, the manufacture of chlorine in mercury cells, coal and other forms of industrial combustion
Ni	83	54	Combustion of heavy fuel oil
Se	31	92	Glass production and combustion for public electricity and heat production
V	477	21	Fuel oil combustion
Zn	339	72	Metal production and combustion in industry

Note: this table is adapted from UK emissions of air pollutants 1970 to 2009 by AEA (2011): available at http://uk-air.defra.gov.uk/reports/cat07/1401131501_NAEI_Annual_Report_2009.pdf

Table 2: Results of Source Apportionment (SA) with different receptor models at industrial sites.

Ref.	Study Area	Setting of Study Area and population	Method of SA	Parameter used for SA	Types of Industry	PM Size	Marker elements for industries	PM conc.: µg/m^3	Source Contribution (%)							
									Combustion (coal, wood, oil, gas, biomass,)*	Marine or other salt source (e.g. road salt)	Vehicle emission (exhaust & non-exhaust)	Secondary aerosol, Regional or long range transport	Crustal matter **	Industry	Incineration or waste Incineration	Un-explained or Others
Hien et al., 2001	Ho Chi Minh City, Vietnam	Industrial, commercial 4.5 million	PCFA	Metals	Small factories	TSP PM_{2-10} PM_2	Ce, Co, As, Cr, Pb, Sb	74 32 16	11 16 18	 18 	6 17 17	 25	77 33 27	4 2 13		2 14
Kumar et al., 2001	Mumbai India	Industrial/ Residential	PCA	Metals, OC/EC, ions, NO2	Medium scale industries	SPM, likely to be TSP	Cu, Mn, Ni	1032-1176	6-11	15	15-18		33-41	6-8		15-17
Oravisjarvi et al., 2003	Raahe, Finland	Industrial, population-17,000	PCA	Metals, Ions	Steel/Mechanical engineering Works	$PM_{2.5}$	Mn, F, Zn, Fe, Ca, Cd, K, Na, Pb, Cl Cu, Mo, Ni, Cr	10				44	7	14		35
Samara et al., 2003	Thessaloniki, Greece	Industrial	CMB	Metals, ions, PAHs	Steel, Oil refineries, metallurgy, cement	PM_{10}	V, Fe, Zn, Pb, Cl, Ca, Na, SO_4, NO_3	-	8-28		47-64		19-29	0-7		-

Chung et al., 2006	Urban Daehwa, Korea	Industrial 1.4 million	PMF	Metals	Soap, cosmetics, metallurgy, plastic, chemicals	$PM_{2.5}$ $PM_{2.5\text{-}10}$	Al, Cl, Cr, Ti, Fe, Co, As, Cu	10 23	36 24	3 9	24 5		2 55	28 2	9 5	
Connell et al., 2006	Steubenville, USA	Industrial, 132,000	PMF	Metals, anions	Coke, Metal Smelting and processing	$PM_{2.5}$	Fe, Mn, Zn, Mg, As, Zn, Cu, Cd, Pb	18	3		20	57	6	13		
Kim and Jo, 2006	Pohang, Korea	Industrial	PCA	Metals	Metal industries	PM_{10}	Cu, Mn, Tl,	76			9		35	10	18	28
Ogulei et al., 2006	Baltimore Supersite, USA	Industrial	PMF	Metals, ions, OC/EC, Gases	Steel, Automotive painting	$PM_{2.5}$	Fe, Cu, Pb		44		10	33	3	2	8	
Querol et al., 2006	Changqian, Wuhan City, China	Industrial 9 million	PCA	Metals, ions, OC/EC	Steel, Petrochemical	PM_{10}	Cd, Bi, Rb, As, Cu, Pb, Sb, Sn and K	197	20		10	16	34	15		5
Gupta et al., 2007	Kolkata, India	Industrial	CMB	Metals, PAHs, Ions	Metal, electroplating	PM_{10} TSP			34 17		47 7		1 52	1		17 24
Cetin et al., 2007	Aliaga, Turkey	Industrial	CMB	Metals, PAHS	Steel	PM_{10}	Zn, Fe, Pb, Mn, Cd	87 w 60 s	25 w 7 s	1 w	7 w		12 s	70w 55 s		26 s
Karar and Gupta, 2007	Kolkata, India	Industrial	PCA-APCS	Metals, PAHs, TC, OC, Ions		PM_{10}	Cr	197	29		45	1		18		7

Gildemeister er, et al., 2007	Dearborn, Detroit, USA	Industrial	PMF	Metals, Anions, OC/EC	Metallurgy, Steel, Oil refinery	$PM_{2.5}$	Fe, K, Mn, Zn, Ca	19	8	4	30	43	12	12		
Chavent et al., 2007	Anglet, South West, France	Industrial 170, 000	Factor Analysis	Metals	Steel	$PM_{2.5}$	Zn, Pb		78	5	9		6	3		
Mazzei et al., 2008	Cornigliano, Genoa, Italy	Industrial	PMF	Metals	Steel	PM_1 $PM_{2.5}$ PM_{10}	Fe, Mn, Zn, Pb	18 19 42	58 40 -	- - 17	9 17 15	11 7 36	7 17 8	7 20 23		6 3 1
Viana et al., 2008b	Castello, Spain	Industrial	PCA PMF CMB	Metals, OC/EC, Ions	Ceramic, petrochemical, organic chemicals	PM_{10}	As, Zn, Pb, Cs, Tl, Zr, Hf, Ce	34		3	10 10 13	25 18	12	48 32 47		42 33 7
Yatkin and Bayram, 2008	Izmir, Turkey	Industrial, 3 millions	PMF CMB	Metals	Iron & steel, cement, minerals	$PM_{2.5}$	Zn, Pb, Mn, Fe, V, Ni	64	7-11	2-3	15 80-81		1 1-3	1-1		70
Amato et al., 2009	Bacelonia, Spain	Industrial, 1.6 million	ME-2	Metals, ions, total carbon	Asphalt, Ferrous and non ferrous smelters, Cement Power plants	PM_1 $PM_{2.5}$ PM_{10}	Pb, Zn, Fe, Mn, Cd	17 28 40	8 6 5	0 3 10	36 32 21	48 26 24	3 21 42	2 2 1		
Amato et al., 2009	Bacelonia, Spain	Industrial, 1.6 million	PMF	Metals, ions, total carbon	Asphalt, Ferrous and non ferrous smelters, Cement Power plants	PM_1 $PM_{2.5}$ PM_{10}	Pb, Zn, Fe, Mn, Cd	17 28 40	8 7 6	0 3 11	30 29 28	53 45 25	0 14 31	3 3 2		

Lodhi et al., 2009	Lahore, Pakistan	Industrial, Urban, 6.6 million	PMF	Metals, ions	Steelworks, Power plants	$PM_{2.5}$	Co, Cr, Fe, Mo, Ni, Sn				5	51	18	8		18
Alleman et al, 2010	Dunkirk, France	Industrial 210, 000	PMF	Metals	Mixed Industrial zone	PM_{10}	Fe, Ca, Si, Mo, As, Cd, Pb, V, Ni, Ti, Zn			12	15		24	37		12
Lim et al., 2010	Daejon, Korea	Industrial 1.45 million	PMF	Metals, ions	Metallurgy, plastic, chemicals, cement	PM_{10}	As, In, Cl, Fe, K, SO_4, NH_4, Pb	86	6		9	23	48	7		7
Xue et al., 2010	Panzhihua, China	Urban/ Industrial	NCMB	Metals, Anions	Iron & steel, metallurgy	PM_{10}	TC, V, Ti, Cr, Mn,	131-179	26		14	23	11	20		8
Zeng et al., 2010	Taiyuan, China	Industrial	PCA/MLR	Metals, ions, OC	Steel, Construction, chemical, energy	PM_{10}	Co, Cr, Fe, Mo, Ni, Sn	305	18		13	16	38	12		3
Mansha et al., 2012	Karachi, Pakistan	Industrial 14 million	PMF	Metals, ions	Steel, Cement, Textile, Refineries, Petrochemical	$PM_{2.5}$	Co, Cr, Fe, Mo, Ni, Sn	84			19	12	16	53		
Pancras et al., 2013	Dearborn, Michigan, USA	Industrial	PMF	Metals, ions, OC/EC	Metallurgy, Steel, Oil refinery	$PM_{2.5}$	Se, SO_2, Fe, Mn, Pb, Cu, Zn, K, Rb	16	4		8	54	13	7	2	
Pancras et al., 2013	Dearborn, Michigan, USA	Industrial	Unmix	Metals, ions, OC/EC	Metallurgy, Steel, Oil refinery	$PM_{2.5}$	SO_2, Fe, Cu, K, Rb	16	3		28	60		14	1	

Farao et al., 2014	Ferrara, Po Valley, Italy	Industrial 132, 000	PMF	Metals, ions, OC/EC		PM_{10} $PM_{2.5}$	As, Cd, Pb, Tl, Zn			5 2	13	40	20 20	10 4		56 27
Taiwo et al., 2014	Port Talbot, South Wales, UK	Industrial 35, 000	ME-2	Metals, ions	Steel	PM_{10} $PM_{2.5-10}$ $PM_{2.5}$	Fe, Mn, Ca, Ni, Cd, Pb, Zn	8 12 20		20 30 28	13 16 16	20 13		14 31 23		33 10 33

Note: NCMB-Nested chemical mass balance, CPF- Conditional Probability Function, PSCF- Potential Source Contribution Function. LMR-Least Multiple Regression, W-winter, S-summer; Sometimes two or more sources were grouped as one factor for example, in Kim and Jo (2006), Lim et al. (2010), Lodhi et al. (2009), Yatkin and Bayram (2008) and Viana et al. (2008b), in which the factor will be counted as "others". For these reasons, readers are strongly advised to read the original articles for more details

*, Different authors used different definition of this combustion source for example, coal, wood, oil, and gas combustion, and biomass burning; they were grouped together for simplicity in this review.**, this category includes all crustal element based source, for example, soil dust, road dust, cement or minerals.

Table 3: Source apportionment with different receptor models at residential sites (selected studies) with a reported industrial contribution.

Authors	Study Area	Setting of Study Area	SA Method	Parameter	PM Size	Marker element for industry	PM conc. (µg/m^3)	Sources Contribution (%)							
								Combustion, coal, wood, oil, (cooking)	Marine aerosol	Traffic (Exhaust and non-exhaust)	Secondary aerosol	Crustal matter	Industry	Waste, Incineration	Others
Castanho, and Artaxo, 2001	Sao Paulo, Brazil	Residential 5.5 millions	APFA	Metals, OC, EC	$PM_{2.5}$	Zn, Mn, Pb, Fe, Ni, S	30 w, 15 s	19 21		28 24	23 17	25 31	5 6		
Almeida et al., 2005	Bobadela, Portugal	Residential	PCA/MLRA	Metals, OC, BC, Anions	$PM_{2.5}$ $PM_{2.5-10}$	Zn, Cu, Sb, Pb	24 16	8 5	8 47	22	25 15	16 20	0.2 0.4		21 13
Alastuey et al., 2007	Tarragona harbour, Spain	Harbour	PCA-MLRA	Metals, Anions	PM_{10}	V, Ni, Mn, Co	40		13	34		17	12		24
Kim et al., 2007	Ohio River Valley, USA	Residential	PMF	Metals, OC, EC, Ions	$PM_{2.5}$	Fe, Mn, Ca, SO_4, Zn, Pb	14			2.5	69	2.5	6		20
Srivastava and Jain, 2008	Delhi, India	Residential 14 millions	CMB	Metals	>1.6µm <1.6µm	Fe, Mn, Cu, Cr, Ni, Pb				29 62		68 36	3 2		
Srivastava and Jain, 2008	Delhi, India	Residential 14 millions	PCA	Metals	>1.6µm <1.6µm					23 86		68 10			
Yatkin and Bayram, 2008	Izmir, Turkey	Sub-urban, 3 millions	PMF	Metals	$PM_{2.5}$	Zn, Pb, Mn, Fe, V, Ni	24		4	12		9			75
Yatkin and Bayram, 2008	Izmir, Turkey	Sub-urban, 3 millions	CMB	Metals	$PM_{2.5}$	Zn, Pb, Mn, Fe, V, Ni	20 w 29 s	13 10	6 10	71 63		8 15	1 2		0.4 0.1
Callen et al., 2009	Zaragora, Spain	Urban	PCA-APCS Unmix PMF	Metals, OC, EC, Ions, PAHs, NH4	PM_{10}		32	13 12	4 10 7	 15 7		56 65 40			27 9 34

Zhang et al., 2013	Beijing, China	urban	PMF	Metals, anions, OC/EC	$PM_{2.5}$	OC, EC, Zn, Mn, and Cr	135	30			26	15	25		4

Note: W-winter, S-summer; Sometimes two or more sources were grouped as one factor, in which the factor will be counted as “others”. For these reasons, readers are strongly advised to read the original articles for more details; Different authors used different definition of this combustion source for example, coal, wood, oil, and gas combustion, and biomass burning; they were grouped together for simplicity in this review

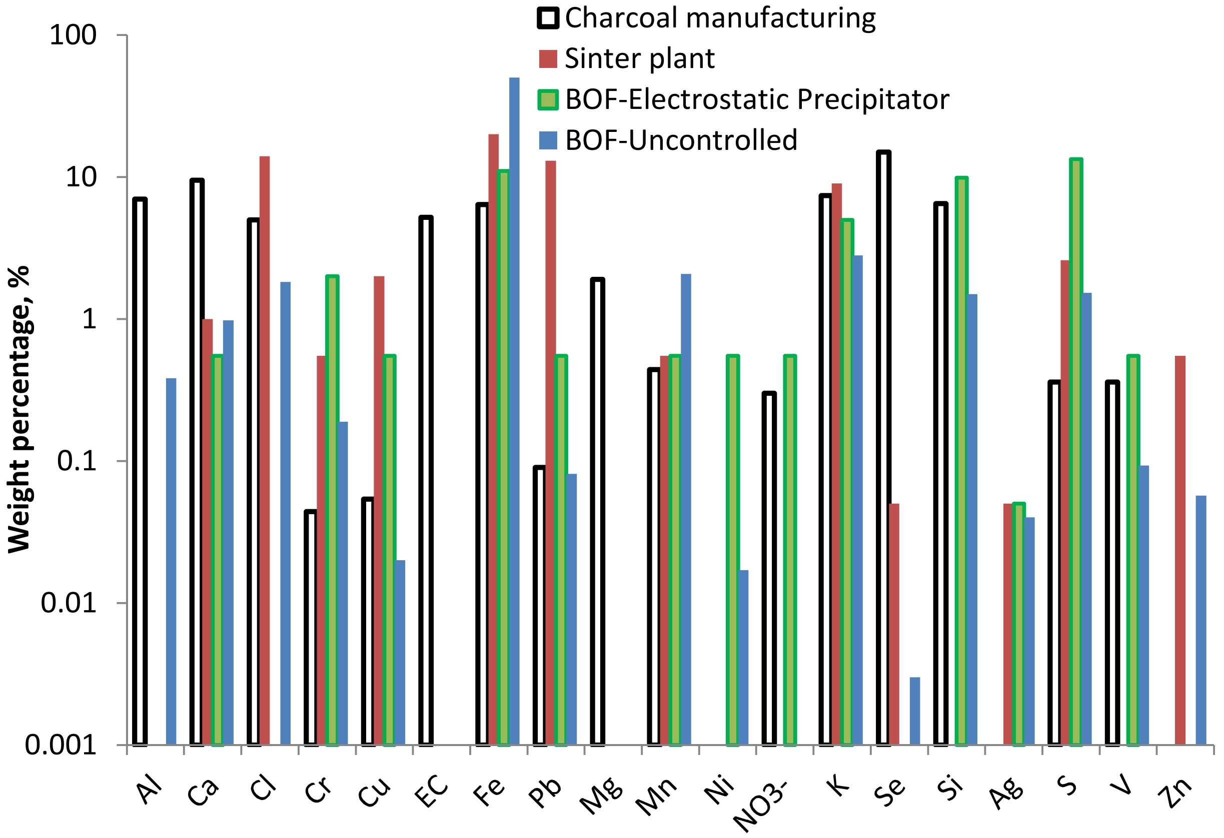
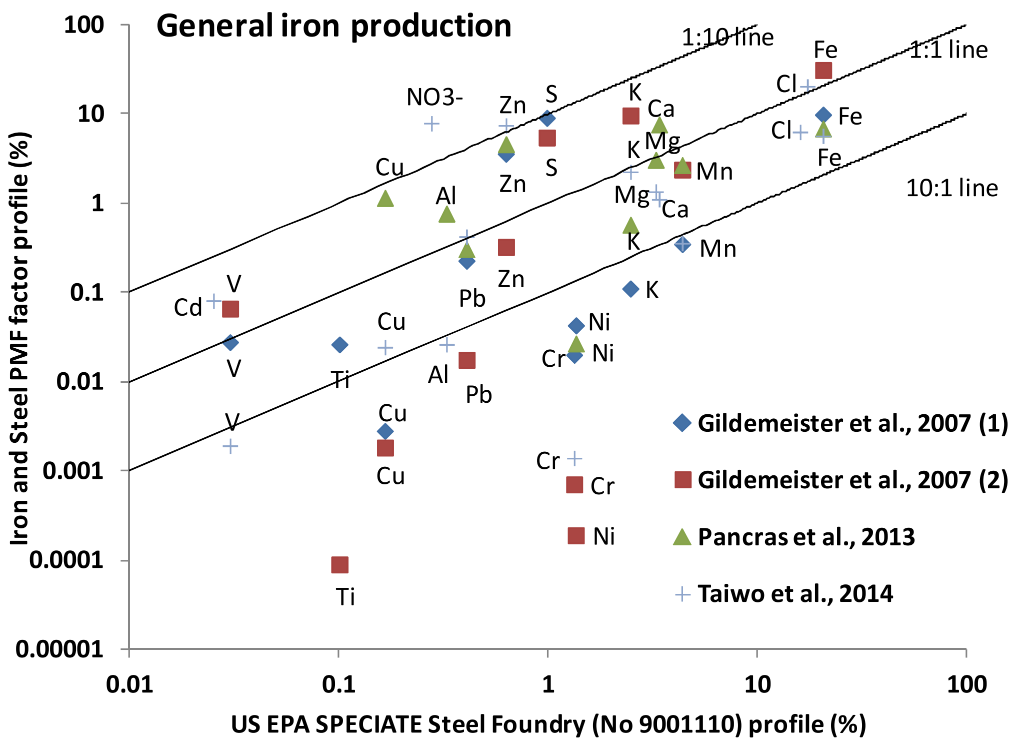
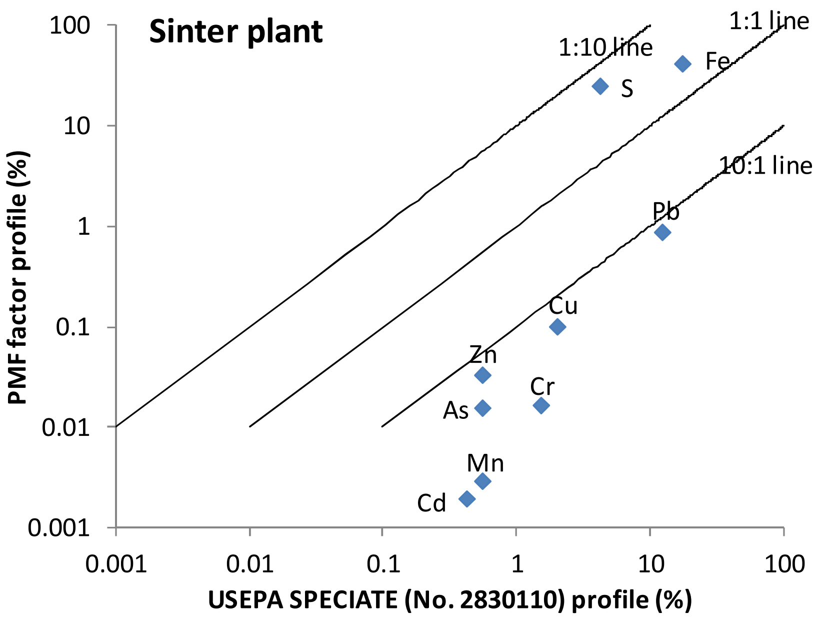


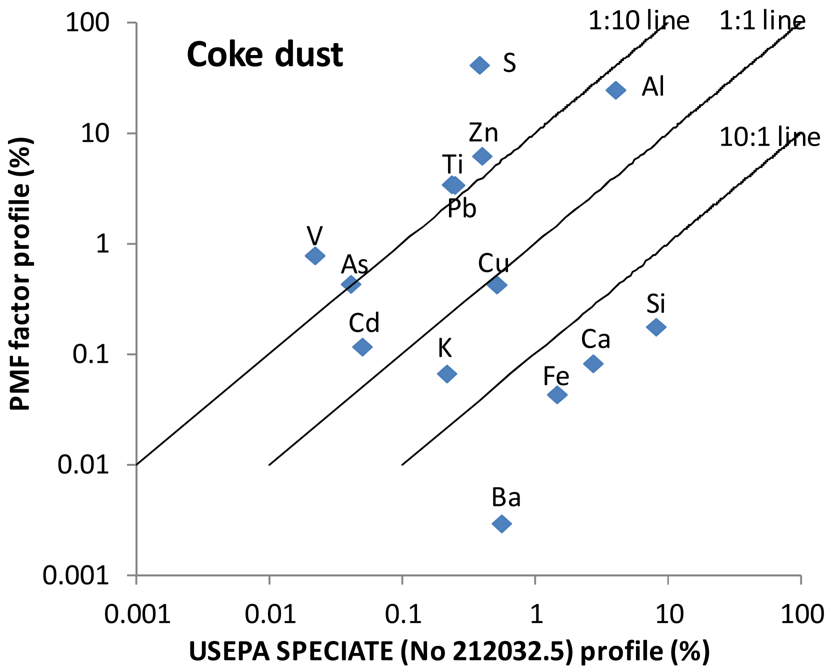
Figure 1: Source profiles of charcoal manufacturing, sinter plant and BOF plant (with electrostatic precipitator and uncontrolled). From US EPA SPECIATE database.


General iron production
1:10 line
1:1 line
10:1 line
Gildemeister et al., 2007 (1)
Gildemeister et al., 2007 (2)
Pancras et al., 2013
Taiwo et al., 2014
Iron and Steel PMF factor profile (%)
US EPA SPECIATE Steel Foundry (No 9001110) profile (%)
100
10
1
0.1
0.01
0.001
0.0001
0.00001
0.01
0.1
1
10
100
Fe
Cl
Fe
Cl
Fe
K
Ca
K
Mg
Mn
Mg
Ca
K
Mn
K
NO3-
Zn
S
Zn
S
Cu
Al
Zn
Pb
Zn
Cd
V
V
Ti
Cu
Al
Pb
Ni
Cr
Ni
V
Cu
Cu
Cr
Cr
Ni
Ti

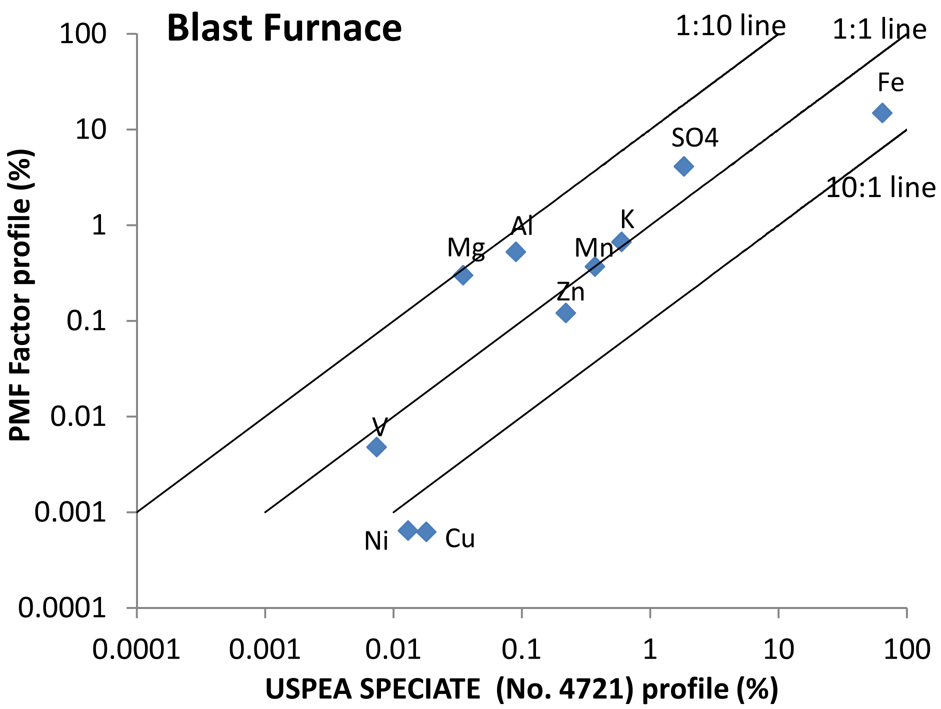
(a)


Sinter plant
1:10 line
1:1 line
10:1 line
PMF factor profile (%)
USEPA SPECIATE (No. 2830110) profile (%)
100
10
1
0.1
0.01
0.001
0.001
0.01
0.1
1
10
100
Fe
S
Pb
Cu
Zn
Cr
As
Mn
Cd

(b)



(c)



(d)

Figure 2: Scatter plots of PMF factor profiles (in percentage) from published studies versus USEPA SPECIATE source profiles for (a) general steel production, (b) sinter plant, (c) coke plant and (d) and blast furnace. In Fig. 2a, Gildemeister et al. (2007) (1): site 1-Allen Park site; Gildemeister et al. (2007) (2): Dearborn site at Detroit industrial area, USA; PMF profile in Taiwo et al. (2014) (Fig. 2a) was a mixed factor comprising Steel 2 (BOS) and Steel 4 (sinter plant); PMF factor profiles in Gildemeister et al. (2007) were kindly provided by the authors; PMF profiles of iron/steel factor from Pancras et al. (2013) were estimated (so carries small subjective error) from concentration of each element (in ng m^{-3}) in Fig. 3 in the original paper and the apportioned iron/steel factor concentration of 0.36 μg m^{-3} (Table 4 of the original paper). PMF factor profiles of sinter plant (Fig. 2b) and coke dust (Fig. 2c) are from Alleman et al., (2010) and that of blast

furnace (Fig. 2d) is from Taiwo et al. (2014). The USEPA SPECIATE blast furnace profile: PM (0-38 μm) from kish graphite from blast furnace process in iron and steel manufacturing. Ni and Ba made negligible contribution to factor Steel 2 and 4 in Taiwo et al. (2014) so were not included in comparison (Fig. 2a); similarly Cr made negligible contribution to factor Steel 1 in Taiwo et al. (2014) so was not included in comparison (Fig. 2d). Please note that some elements were reported in USEPA SPECIATE source profiles but not in PMF factor profiles; and vice versa. In those cases, the data could not be shown in the figures.

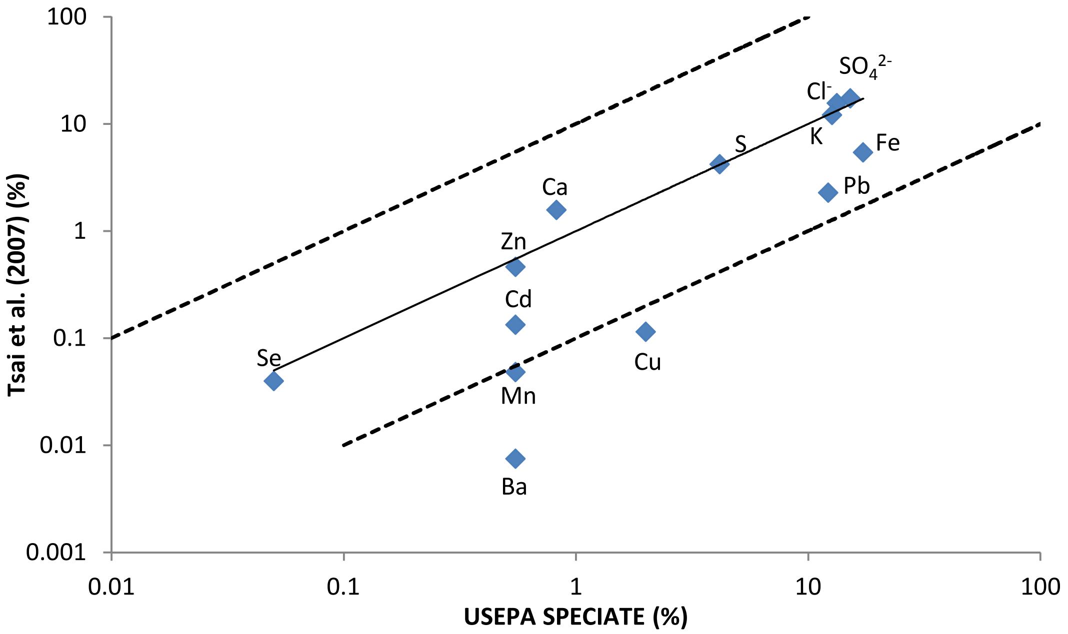


Figure 3: Regression plots of USEPA SPECIATE vs Tsai et al. (2007) source profiles for the sintering process in the steel industry.

A Review of Receptor Modelling of Industrially Emitted Particulate Matter

Adewale M. Taiwo, Roy M. Harrison and Zongbo Shi

HIGHLIGHTS

- Industrial processes have been identified as an important source of airborne PM.
- PM from different sites within the same industry may vary appreciably in composition.
- PM from different processes within the same industrial site can differ substantially.
- Local source profile measurements are needed for industrial PM source apportionment.