CHEMICAL ENGINEERING TRANSACTIONS

VOL. 91, 2022

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Valerio Cozzani, Bruno Fabiano, Genserik Reniers

ISBN 978-88-95608-89-1; **ISSN** 2283-9216

DOI: 10.3303/CET2291026

A Comprehensive Approach to Establish the Impact of Worksites Air Emissions

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Worksite activities are time-limited events associated with continuous releases of airborne pollutants, such as carbon monoxide, particulate matter, and NOx, and they impact potentially vast areas. The side-effects on the environment can be severe, and they are subject of literature studies, with the final aim of proposing solutions that may improve the management of air emissions. No general assessment method or approach is yet available to estimate their effects on the environment and workers' health. In this work, a general procedure that can be potentially applied to every type of worksite is proposed (i.e., construction sites, upgrading of chemical plants, road sites, etc..). The approach involves a detailed assessment of emissions and their expected pollutant concentrations. A dedicated mathematical model has been defined to assess pollutant emissions over time, consistent with all the different phases of foreseen activities. Emissions are defined on base of the GANTT descriptions of the activities and air pollutant dispersion is simulated with a dedicated model. Finally, the obtained results are evaluated against air quality thresholds as defined by laws and conditioning the human health risks for workers and citizens potentially exposed to pollutants.
Keywords: Atmospheric pollution, CALPUFF, Environmental impact, Worksites

1. Introduction

Air quality is among the most important environmental issues for a more sustainable future. The number of factors that impact the amount of pollutants in the atmosphere is countless, including both anthropogenic and natural causes. For what concerns anthropogenic factors, any activity should follow specific constraints (according to both national and international standards) for airborne pollutant emissions. In Europe, the main standard regulating airborne pollutant concentrations is the Directive 2008/50/EC, which defines the maximum allowable levels for human and vegetation health. It is well-known that atmospheric pollution is greatly impacted by transport and industry, which consist in constant sources of emissions. However, even short-term activities such as worksites may severely impact air quality. Lepert and Brillet (2019) published a work where they highlighted the increased emissions of greenhouse gases associated with worksites for maintenance and improvement of traffic roads. Also, many sectorial studies have been performed on the modelling and the assessment of pollutant emissions from specific sites. Giunta et al. (2019), noted the potential impact due to the expected growth of the road constructions around the world, and demonstrated that in the worksites of bridges, earthworks and tunnels the overall emissions can be 5 times higher than the emission of storage and concrete production worksites. In a more recent work (Giunta, 2020), the impact of a motorway construction project in Italy was analyzed, and it was shown how deeply can such activities impact air quality, threatening workers, civilians, and environment health. Such analyses are usually considered negligible for smaller activities, and they remain a subject of pure research. This is due to an underestimation of the effects of small worksites and to the lack of simple and general methods dedicated to these purposes. In this work, we propose a potentially general approach to estimate the impact of a worksite, with particular attention to the assessment of human health risk for workers and citizens exposed. The major novelty represented by this model is the generalization of the method, since most of the works presented in the current literature are very specific, involving studies on road construction sites or building sites only. The model starts with a collection of raw data, including operating machine, excavations information, and transportation. Such data are then

Paper Received: 23 February 2022; Revised: 5 April 2022; Accepted: 15 May 2022
Please cite this article as: Barozzi M., Dimauro C., Scotton M.S., Copelli S., 2022, A Comprehensive Approach to Establish the Impact of Worksites Air Emissions, Chemical Engineering Transactions, 91, 151-156 DOI:10.3303/CET2291026

elaborated with the use of Gantt diagrams, which are a very used tool when handling with worksite planning and validate models and emission factors to describe particulate matter, NOx, SOx and CO emissions. In this way it is possible to both assess global emissions and emission sources. After a proper detection of source types, dispersion modelling can be carried out. While pollutant dispersion can be estimated with several available mathematical models, the use of Calpuff is highly recommended, due to its capacity of representing point, linear and areal sources with a discontinuous functioning, and the capability of describing phenomena such as atmospheric turbulence or thermal inversion. From results, with the use of threshold values, exposure maps for workers can be elaborated.

2. Methodology

The method proposed is summarized in Figure 1. The main idea consists in estimating emissions at different levels: at first, according to worksite characteristics, including information about activity types, machines and transportation means, it is possible to estimate the overall emissions. Using information from the Gantt diagram and work shifts, it is also possible to deduce the emissions profile overtime. Note that such information is usually always available, since they are deeply connected to the activity itself.

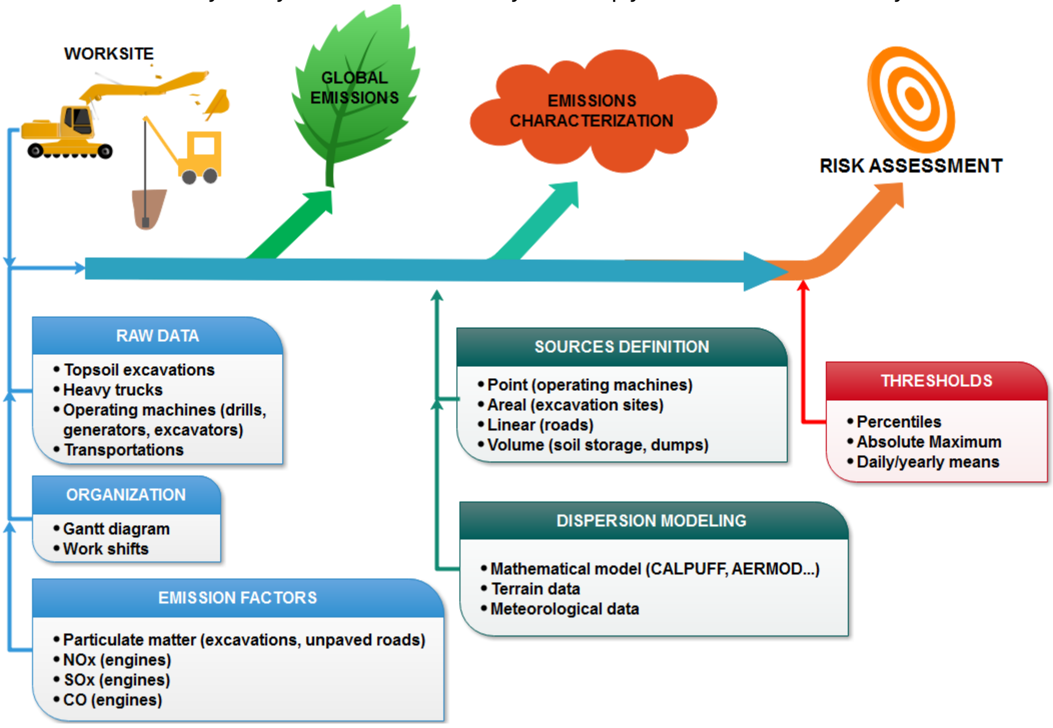

Figure 1: Scheme of the proposed model

This first step requires also dedicated sub-models to estimate pollutant emissions. The analysis is carried out for the most common airborne pollutants from engines and excavations: particulate matter ($PM_{2.5}$ and PM_{10}), NOx, SOx, and carbon monoxide. Once sub-models and worksite main information are set, it is possible to estimate global and overtime emissions, as it will be shown later. This is already an important information, which can be helpful in defining what are supposed to be most impactful activities for the work. However, it is now possible to evaluate the emission profiles. In this case, it is necessary to associate each source to its category, which can be a point, areal or linear source. Point sources are more suitable for single operating machines, such as drills and generators. Areal sources define well topsoil excavations and aggregates storage. Linear sources are both paved and unpaved roads, that require also specific sub-models to establish the correct particulate matter suspension.

2.1 Emission factors for engines

The pollutants produced by the means of excavations, transportation, and other operations, such as welding generators, are essentially associated with the combustion processes of the related engines. Actually, it is possible to split between immobile equipment, such as drills, generators compressors or excavators, and mobile ones, like heavy trucks. For what concerns the first category, the global emissions can be estimated with the use of the database SCAB (South Coast Air Basin), Fleet Average Emission Factors, developed from the South Coast Air Quality Management District. Such a database is a very useful tool, which takes in account the evolution of emission thresholds over the year (the current database covers the period 2007-2025). For each equipment, the emission factor can be estimated thanks to the relation expressed by Eq. 1.

$$E_i = H \cdot EF_i \tag{1}$$

E is the total emission in grams per day for a i-th pollutant, H corresponds to the hours per day of equipment operation and EF is the off-road mobile source emission factor by equipment category or horsepower-based equipment category in grams per hour. Table 1 shows the current values for Drill Rigs. As it can be noticed, equipment power is required in order to properly assess the factor.

Table 1: Example of emission factors EF for Drill Rigs (calculated from 2020 values) (AQMD, 2021)

	MaxCV	ROG [g/h]	CO [g/h]	NOx [g/h]	SOx [g/h]	PM [g/h]	CO_2 [g/h]	CH_4 [g/h]
Bore/Drill Rigs	15.2	4.57	23.96	28.61	0.06	1.12	3924.79	0.41
	25.35	6.15	20.69	38.50	0.06	1.54	4971.40	0.56
	50.69	10.55	63.73	62.11	0.12	2.77	8896.19	0.95

For what concerns mobile sources, such as heavy trucks or simple buses and cars used to move operators on the worksite every day, two databases can be used. For Heavy-Duty Trucks, the Environmental Protection Agency developed a database of emission factors for trucks (EPA, 2008), which defines the emission factors for VOC, CO, NOx, $PM_{2.5}$ and PM_{10} for diesel or gasoline. Factors are classified into 8 classes (from IIb to VIIIb) depending on the total weight (ranging from 3856 kg to >27 tons). Daily emissions are estimated by Eq. 2:

$$E_i = D \cdot EFM_i \tag{2}$$

E is the total emission in grams per day for a i-th pollutant, D corresponds to the kilometers run per day and EFM is the off-road mobile source emission factor by truck category in grams per kilometer.
For cars and buses, it is possible to use Euro VI norm (or an equivalent one for older vehicles), which functions in the same way, but with different EFM_i values.
Also, PM_{10} can be emitted from transits on unpaved roads, as a result of interactions among tires and dusty surfaces. EPA proposes the relationship expressed by Eq. 3 to estimate the additional dust production from transit on unpaved roads:

$$E_{U,PM10} = D_u \cdot k \cdot \left(\frac{s}{12}\right)^a \cdot \left(\frac{W}{3}\right)^b \tag{3}$$

$E_{u,PM10}$ is the PM10 emission factor in grams per day, D_u is the daily distance ran on unpaved roads, k, a, b are empirical constants depending on the particulate size, s is the surface material silt content (%), W is the mean vehicle weight (tons).

2.2 Emission factors due to topsoil excavations

The presence of excavations determines dispersions of fine dust associated with the movement of land and its storage. The contaminants released associated with this activity is essentially associated with the finer fraction of powders as the heavier ones are deposited relatively quickly and near the release points. The finer fractions such as $PM1_0$ and $PM_{2.5}$, in addition to having an interest from the point of view of environmental contamination and impacts on human health, are able to remain suspended in the air and be transported by local anemological processes.
The estimate of fine particulate emissions is carried out with reference to the AP 42 from EPA (EPA, 2007), which reports the emission references as a function of the tons of earth removed. The emission coefficient is therefore defined as grams of fine dust released per ton of earth removed. The emission factor, shown in Eq.4, is also estimated considering the effects due to the intensity of the wind and the degree of humidity of the soil.

$$E_i = 1.6 \cdot k \cdot \left(\frac{U}{2.2}\right)^{1.3} \cdot \left(\frac{M}{2}\right)^{-1.4} \tag{4}$$

Where E is emission factor expressed in g of dust per ton of material removed (on daily basis) for the i-th dust average size, U is the wind speed, in m/s; M is the percentage content of soil moisture, ranging from 0.25 to 4.8% and k is a factor that depends on the size of the particulate.
After excavations, removed soil is usually stored. According to the literature, the emissions resulting from the erosive effects due to the action of the wind of different intensity on piles of excavated material are low. Vegetation covers typically form on the surface and a crust typically forms, that is a layer of soil characterized by a low degree of humidity, which limits the mechanical actions of the wind. However, the emission potential increases each time the surface is altered, providing the pile with a new surface of erodible material.
In general, the storage cycle of material in heaps requires that the material is periodically added or subtracted, modifying the old surface layer, inactive from the point of view of the emission potential, reactivating the erosive capacity of the wind. The daily emissions of the pile are therefore directly proportional to the number of changes in the crust per day. It can also be observed that the average atmospheric wind speed (even on an hourly basis) is not sufficient to generate a significant erosion of the surface of the accumulated materials and it is therefore necessary to refer to the maximum intensity of the gusts of wind and their frequency in the period between one disturbance intervention and another. In summary, the emissions related to dusting by the heap depend on factors such as the number of disturbances per day, the age of the heap, its moisture content, the portion of fine aggregates and the anemological conditions of the site. Emissions due to wind erosion from piles are characterized in AP-42, Chapter 13.2.5 (EPA, 2007) which treats the emission potential of the single pile as a function of a series of factors. In particular, the daily emission rate is given by Eq. 5:

$$E_{p.i} = 1000 \cdot EF_{p.i} \cdot a \cdot mov \cdot H \tag{5}$$

Where E_p is the amount of dust lifted in g/day, i refers to each particulate matter considered (PM_{10}, $PM_{2.5}$), $EF_{p,I}$ is the areal emission factor in kg/m²,a is the surface of the moved area in m³, mov is the number of movements / hour and H is the total number of hours worked per day.

3. Model application

3.1 Global emissions

Global and overtime emissions are estimated by means of Gantt diagrams, activities performed and operating machines. Gantt diagrams are structures widely used worldwide to define the timetables of a worksite. They are generated by associating the different activities in which the work is organized with the expected time they are supposed to last. To the scope of this model, it is possible to associate a Gantt diagram to a Boolean variable, where 1 consists of the presence of the specific activity at a given time step. Table 1 represents a translation of a classic Gantt diagram into a Boolean matrix, with dimensions of na x nt, where na is the total number of activities involved, and nt is the number of time steps identified. Usually, each time step has the same length (months or 30 days). This modified Gantt diagram is a matrix called G.

Table 1: Example of Gantt table (in this case, na=3 and nt=4)

	t1	t2	t3	t4
Activity 1	1	1	0	0
Activity 2	0	1	1	1
Activity 3	0	0	0	1

From this table, it is possible to deduce specific global emissions with the help of additional matrices. It is possible to introduce a matrix (called P), structured in the following way: each row represents the activities listed in the Gantt table (so the number of rows is equal to na), and each column represents all the specific operating machines, trucks, excavations present during the whole activity. Now, the numbers in the matrix are the total number of machines etc. used. Table 2 represents an example: in this case, a single drill is used during activity 1, no one is used in phase 2, and 2 are used in the final phase.

Table 2: Example of P a matrix translated into a table

	Drill	Excavations	Heavy trucks
Activity 1	1	0	2
Activity 2	0	1	0
Activity 3	2	1	2

An additional matrix, called E, must be finally introduced. In this case, the matrix contains information about the emission factors which were calculated according to dedicated models. In this case, the rows contain the equipment listed already in the P matrix, and the columns contains the pollutants chosen (in this case, 5 pollutants are identified). An example is reported in Table 3.

Table 3: Example of a E matrix translated into a table (each emission factor is referred to data for the specific operating machine/activity)

	CO	NOx	SOx	$PM_{2.5}$	PM_{10}
Drill	E_{CO}	E_{NOx}	E_{SOx}	$E_{PM2.5}$	E_{PM10}
Excavations	E_{CO}	E_{NOx}	E_{SOx}	$E_{2.5}+E_{p2.5}$	$E_{10}+E_{p10}$
Heavy trucks	E_{CO}	E_{NOx}	E_{SOx}	$E_{PM2.5}$	$E_{PM10}+E_{U,PM10}$

Now it is possible to estimate global emissions overtime exploiting simple matrix operations. The matrix Et is now defined, according to Eq. 7.

$$E_T = G' \cdot (P \cdot E \cdot t) \tag{7}$$

Where ‘ indicates the transposed matrix and t is the number of days for each time period identified in the Gantt diagram (if defined in months, usually t can be considered equal to 24 days). The matrix E_T contains important information: due to its structure, it contains for each time step defined in the Gantt table the overall emissions for each pollutant. In this way, it is possible to instantly identify the potentially most critical time steps of the worksite.

Table 4: Example of a E_T matrix translated into a table

	CO [g]	NOx [g]	SOx [g]	PM2.5 [g]	PM10 [g]
t1	$t\sum(E_{CO,1})$	$t\sum(E_{NOx,1})$	$t\sum(E_{SOx,1})$	$t\sum(E_{PM2.5,1}+ E_{2.5,1}+E_{p2.5,1})$	$t\sum(E_{PM10,1}+ E_{10,1}+E_{p10,1})$
t2	$t\sum(E_{CO,2})$	$t\sum(E_{NOx,2})$	$t\sum(E_{SOx,2})$	$t\sum(E_{PM2.5,2}+ E_{2.5,2}+E_{p2.5,2})$	$t\sum(E_{PM10,2}+ E_{10,2}+E_{p10,2})$
t3	$t\sum(E_{CO,3})$	$t\sum(E_{NOx,3})$	$t\sum(E_{SOx,3})$	$t\sum(E_{PM2.5,3}+ E_{2.5,3}+E_{p2.5,3})$	$t\sum(E_{PM10,3}+ E_{10,3}+E_{p10,3})$
t4	$t\sum(E_{CO,4})$	$t\sum(E_{NOx,4})$	$t\sum(E_{SOx,4})$	$t\sum(E_{PM2.5,4}+ E_{2.5,4}+E_{p2.5,4})$	$t\sum(E_{PM10,4}+ E_{10,4}+E_{p10,4})$

3.2 Emission profiles

Once global emissions have been identified, it is possible to proceed forward by resolving the concentration profile overtime on the zone interested by the worksites. This can be carried out by applying a dedicated mathematical model suited for simulating airborne pollutants dispersion. The Environmental Protection Agency regularly uploads recommended mathematical models to estimate (EPA, 2017). Based on the authors knowledge and experience, for these kinds of activities both Gaussian models (Copelli et al., 2019) and Lagrangian ones (such as CALPUFF), are suited for a proper emissions profile determination. A correct implementation of such codes requires a series of necessary steps, which include: geological characterization of the simulated zone, meteorological data assessment, emissions characterization. Emission sources definition will be focused on, since the other steps can be completed with the use of well-known database and models.

Point emissions are single machines, such as drills, excavators. They must be simply placed at the location they are supposed to be placed, and the emission factor (usually in g/h) must be defined. Such data are already known from the matrices E and P. Areal emissions are represented by excavations, in terms of both pure excavation operation and extracted soil stacked. In this case, the emission factor should be expressed in $g/h/m^2$, so information about excavation site size must be recovered or deduced. Finally, linear emission are mainly roads, both paved and unpaved. In this case, the emission factors should be divided into the length of the roads used each day.

Once the model is resolved, concentration profiles overtime can be evaluated, and during post-processing important data can be evaluated to continue with the risk assessment, such as percentiles, time weighted means and absolute maxima.

3.3 Risk assessment

Methodologies and techniques used in health risk assessment are firmly established (WHO, 2021). The assessment of human health risk requires identification, compilation and integration of information on the health hazards of a chemical, human exposure to the chemical, and the relationships between exposure, dose and adverse effects. The purpose of the hazard identification step is to determine the hazardous properties of the chemical released during the with all the different phases of worksite activities.

Hazard characterization and related guideline value identification is used to obtain a reference value for the chemical that matches the route and duration of exposure (for example, inhalation and long-term exposure).

Guidance and guideline values are normally the result of hazard characterizations and involve dose–response assessment. Then, through an exposure assessment it is possible to define the most likely routes, pathways, duration, frequency and intensity of exposure that can be relevant for the potentially exposed workers and population.
In the final step of the hazard identification, hazard characterization and exposure information are combined to yield a statement of risk. The risk for the exposed population/operators can depend on many aspects, but the most important are: concentration of the toxic chemical at the point of exposure, type of exposure and the intake pathway, duration of exposure (from minute to decades), toxicity of the released substance distinguished in chemical that have chronic effects and cancerogenic impacts, and vulnerability of the exposed person.
Considering the chemicals that can induce chronic effect, the risk is calculated considering the dose assumed over a specific period. This value can be compared with the reference threshold of tolerance (e.g. in the short term: Immediately Dangerous To Life or Health (IDLH) Values; Threshold Limit Values (TLV), Permissible Exposure Limit (PEL), or in the long period: Reference dose (RfD) or Reference concentration (RfC)). Note that the definition of dose can be estimated with the knowledge of the concentrations at which a human subject is exposed. So, the modeling of pollutant dispersions can be easily improved by adding specific receptors, for which a concentration overtime curve can be defined. Hence, the expected daily dose can be easily defined.

4. Conclusions

In this work, a theoretical general method to estimate environmental and health impact of worksites is proposed. The method involves well-established literature methods for the establishment of emission factors and used information which are already known at the level of worksite operations definition and assessment. With a good structure, global emissions are easily identified with the use of simple matrix operations. The same information can be also easily used to implement a mathematical model to address the level of exposure of specific receptors, leading to a precise health risk assessment for workers or exposed citizens. Clearly, a description of all aspects that characterize the risk assessment activities is more complex and requires a more extensive description. However, it is reasonable to assume that the current level of detail is sufficient to highlight how the risk assessment associated to the release of toxic substances during worksite activities may be a valid approach to support decision-making process about the definition of worksite management strategies that can mitigate and minimize the potential risk for workers and people living nearby the worksite. It will be interesting for future works to include comprehensive research with a real case study, along with in-site air contaminants analyses, in order to validate the effective potential of the proposed method.

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