Ann. Occup. Hyg., Vol. 55, No. 9, pp. 989–1005, 2011

doi:10.1093/annhyg/mer072

Classification of Occupational Activities for Assessment of Inhalation Exposure

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Received 15 April 2011; in final form 12 July 2011; published online 15 September 2011

There is a large variety of activities in workplaces that can lead to emission of substances. Coding systems based on determinants of emission have so far not been developed. In this paper, a system of Activity Classes and Activity Subclasses is proposed for categorizing activities involving chemical use. Activity Classes share their so-called 'emission generation mechanisms' and physical state of the product handled and the underlying determinants of emission. A number of (industrial) stakeholders actively participated in testing and fine-tuning the system. With the help of these stakeholders, it was found to be relatively easy to allocate a large number of activities to the Activity Classes and Activity Subclasses. The system facilitates a more structured classification of activities in exposure databases, a structured analysis of the analogy of exposure activities, and a transparent quantification of the activity emission potential in (new) exposure assessment models. The first use of the system is in the Advanced REACH Tool.

Keywords: determinants of exposure; exposure assessment methodology; exposure modeling; REACH

INTRODUCTION

Exposure at the workplace is complex and many factors influence the exposure level at a given workplace in a given situation (Kromhout *et al.*, 1993). Tielemans *et al.* (2008a) recently elaborated on a source–receptor model for inhalation exposure proposed by Cherrie and Schneider (1999), to develop a conceptual model, using source factors and exposure modifiers, that can be used for building a predictive exposure model. This model describes four main stages in the exposure pathway: separation of gas or vapour molecules or solid particles from the parent material (i.e. the source), followed by dispersion of the contaminant through the work area, loss of contaminant into various sinks, and then uptake by the receptor (i.e. the individual worker). Based on this conceptual model, a list of nine mutually independent principal modifying factors (MFs) was proposed for prediction of inhalation exposure levels.

One of the principal MF is 'activity emission potential' that describes the potential of an activity to generate emissions into the work environment. Different features of an activity are relevant in terms of emission, such as (i) the type and amount of energy transfer during an activity, (ii) the scale of use, and (iii) the extent of contact between product and

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adjacent air (the product-to-air interface). This complexity is illustrated by the fact that activities are often clustered in non-precise classes in exposure models, for example 'non-dispersive use' and 'low dust techniques' in the EASE model (Tickner *et al.*, 2005).

A systematic classification system would help avoid ambiguity in characterizing or quantifying the activity emission potential. An activity classification has previously been developed for clustering dermal exposure situations and used in a dermal exposure model (Marquart *et al.*, 2006; Van Hemmen *et al.*, 2003; Warren *et al.*, 2006), but such a classification is currently lacking for inhalation exposure. Within REACH, the concept of 'process categories' or PROCs has been developed (ECHA, 2010). The PROCs are part of the 'use descriptors' that are intended to help structure supply chain communications and hence can be used to derive a more systematic description of identified uses in REACH dossiers (ECHA, 2010). They evolved from the system for describing workplace exposure scenarios first proposed in the ECETOC TRA (ECETOC, 2004) and have subsequently been extended using the handling categories used in Stoffenmanager (Marquart *et al.*, 2008) and in the metals industry. The PROCs now form one starting point for the ECETOC TRA (ECETOC, 2009; Money *et al.*, 2007). However, these PROCs are not exclusively based on the emission process. They combine activity-based categories, such as 'rolling and brushing' with more generic descriptions, such as 'Use in closed, continuous process with occasional controlled exposure'.

In the present paper, a new clustering scheme of 'Activity Classes' is proposed for inhalation exposure. This scheme provides a method for structuring activities into generic groups characterized by processes with similar emission generation mechanisms and it can be helpful in the efficient storage of exposure data and may improve the identification of analogous data for modeling purposes. In addition, the Activity Class concept should assist in the quantification of the activity emission potential as part of the Advanced REACH Tool or ART (www.advancedreachtool.com).

ACTIVITY CLASS CONCEPT

The activity emission potential depends on various combinations and types of energy transfer, scale, and product to air interface, as discussed by Tielemans *et al.* (2008a). An 'activity' is defined as a specific process step with handling characteristics that differentiate it from other process steps. A simplified description of the paint production process, for example is as follows: liquids are pumped into a mixer (activity 1), solids are added (activity 2), the mixture is mixed (activity 3), and finally it is filled into cans (activity 4). An overview of general definitions used in this paper is given in Table 1. In practice, it may not always be possible to strictly distinguish different activities and a pragmatic approach is used.

A successful classification system of Activity Classes will have the following necessary characteristics:

1. All activities in an Activity Class must be capable of being modeled using the same underlying determinants for activity emission potential.
2. An activity can only be assigned to one Activity Class.
3. The number of Activity Classes should be much less than the number of activities to be clustered.

It is important to note that an Activity Class is not a group of activities with similar exposure levels, comparable to the so-called homogeneous exposure group concept (Rappaport, 1991). Emission rates and exposure levels within an Activity Class can be very different, but the influence of the activities on emissions within one Activity Class can be described by a unique set of determinants. For example, dumping of 1 kg of powder or dumping of 1000 kg of powder are assigned to the same Activity Class, while these activities would clearly lead to different exposure levels if all other operational conditions and risk management measures were the same.

The clustering of activities into a limited number of Activity Classes within ART is based on two main components: (i) the type of emission generation mechanism and (ii) the physical state of the product handled during an activity (solid, liquid). The combination of these components enables a structured distinction between types of activities in terms of their underlying determinants of emission. 'Emission generation mechanism' is a pragmatically described mechanism by which a particular type of energy transfer (as described in Tielemans *et al.*, 2008a) leads to release of a substance from the parent material or the surface to which the substance was attached. The various emission generation mechanisms will be discussed in the following section. Details of the derivation of Activity Classes will be given in a subsequent section.

EMISSION GENERATION MECHANISMS AND PARAMETERS ASSOCIATED WITH THE AMOUNT OF ENERGY TRANSFERRED

A number of emission generation mechanisms have been distinguished by the authors. A recent publication by the UK Health and Safety Executive (HSE, 2008)

Table 1. Glossary of terminology used in this manuscript

Activity	A specific process step with handling characteristics that differentiate it from other process steps
Activity Class	Generic groups of activities for which the same emission generation mechanisms are relevant and for which ultimately the same parameters are used in estimating the activity emission potential
Activity Subclass	Subgroup of activities within an Activity class with the same parameters describing the underlying determinants for activity emission potential
Activity emission potential	Describes the potential of the activity to generate exposure and is determined by the following characteristics: type and amount of energy transfer, product to air interface, and scale
Emission generation mechanism	This is a pragmatically described mechanism determined by a number of physical phenomena (that are described by exposure determinants) by which a particular type of energy (see above) leads to release of a substance into the air surrounding the parent material or the surface to which the substance was attached
Energy transfer	A substance is released from the parent material or from a contaminated surface because of energy transfer. Various types of energy transfer are relevant: i.e. motive forces, gravitational and impaction forces, friction, pressure drop, heat
Exposure determinant	A physical phenomenon influencing the exposure level. In the scope of activity emission potential, the exposure determinant influences the emission of the substance. An exposure determinant cannot necessarily be easily given a value or score because it may be too complex to measure, observe, or estimate
Parameter	A pragmatic representation of one or more exposure determinants. The value of a parameter can be measured, observed, or estimated. One parameter can represent more than one exposure determinant. The parameters are used for deriving activity emission potential scores in the ART model.
Process	A process is, in this scope, a combination of activities that leads to a required end result. An example of a process is, e.g. 'producing a batch of adhesives'
Product	A chemical product, consisting of either a pure chemical component or a mixture of ingredients where the function of the product is not largely governed by its shape: e.g. a powder, granule, or pelletized product or a liquid.
Product to air interface	Relative extent of interaction of a substance with adjacent air during an activity. This is large if a large fraction of product is in contact with adjacent air, while it is low if only a small fraction is in contact with adjacent air
Scale	Provides information on the total amount of substance available for emission
Solid object	A solid form, consisting of one or more chemical components, whose function is largely governed by its shape

was used as a starting point. In the HSE document, 12 'processes' with their 'exposure creation mechanisms' are described. Some of the 'sources', however, are not fully exclusive of each other. The source 'rotating tools and parts', for example includes 'sanders', while there is also a source called 'abrasion' that also includes 'sanding'. Furthermore, the 'exposure creation mechanisms' in the HSE document were not all considered to be sufficiently descriptive of the physical processes leading to emission. For example, the exposure creation mechanism for 'Hot (and cold) processes' is described as: 'Hot sources—fume rises, expands, cools and mixes with the room air. Cold sources—the contaminant sinks'. This does not really indicate how the fume is formed, i.e. that substances evaporate from a solid or liquid product. Because the authors wanted a system more directly related to physical phenomena determining emission and giving a better differentiation between classes, the 'sources' and 'exposure creation mechanisms' of the HSE document were not used as such, but generic 'generation mechanisms' were based on these 'processes' and 'exposure creation mechanisms'. The process 'sweeping' in the HSE document was, e.g. replaced by the generation mechanism 'movement' and the processes 'rotating tools/parts' and 'abrasion' were translated to one generation mechanism 'abrasion'. In this way, the descriptions in the HSE document were translated to more generic 'generation mechanisms'.

The relation between activities, Activity Classes, generation mechanisms, exposure determinants, parameters and activity emission score can be described by a number of rules.

1. An Activity Class has one or more relevant generation mechanisms that are relevant for all activities within the Activity Class.
2. An emission generation mechanism is related to one or more physical phenomena that together determine the emission of the substance. Such a physical phenomenon is called an 'exposure determinant' in the scope of this paper.
3. To enable the calculation of activity emission potential scores in the ART model, the exposure determinants should be quantified somehow. This is done via one or more parameters, which are pragmatic representations of the exposure determinants. The parameters are capable of being measured, observed, or estimated, while some of the exposure determinants themselves are too complex to be measured, observed, or estimated.
4. One parameter may relate to one exposure determinant, but in some cases, a set of exposure determinants together is described by one parameter.
5. The parameters are in general categorical. For the calculation of activity emission potential scores in ART, each category is given a specific score and the scores for different parameters of an Activity Class are multiplied.

The relations between these different 'entities' are illustrated in Fig. 1.

In the end, a specific combination of parameters quantifying a generation mechanisms in a specific way forms an Activity Class. When the same generation mechanisms are relevant, but the quantification of the emission via parameters is different, this leads to different Activity Classes. The Activity Classes 'Handling of contaminated objects (contaminated with liquids)' and 'spreading of liquid products' are driven by the same emission generation mechanisms but are quantified differently. So this results in two different Activity Classes.

In some cases, mostly for pragmatic reasons, e.g. to increase the recognizability for exposure assessors, Activity Classes have been subdivided into a number of Activity Subclasses.

The Activity Classes with their Activity Subclasses, relevant emission generation mechanism(s), and examples of activities are given in Table 2.

Pressure difference

Pressure difference is the driver of and main type of energy transfer involved in the emission of liquids and solids in spray and vacuum transfer processes. Pressure difference can also be used as specific parameter for assessing the amount of energy transferred. For spray applications, this parameter can be expressed as 'spray pressure' (Brouwer *et al.*, 2001; Carlton and Flynn, 1997; Tricou and Knaziac, 2005).

Evaporation

Evaporation is a major mechanism by which liquid substances are emitted into the air surrounding the liquid. The rate of evaporation generally depends on the (partial) vapour pressure of the substance under the conditions of use. The partial vapour pressure of a substance is influenced by the temperature of the product and its composition. The basic type of energy transfer for this emission generation mechanism is therefore 'thermal energy' and the temperature of a liquid product at the site of emission is therefore a parameter of amount of energy transferred. In case that evaporation occurs in an enclosed system, a secondary mechanism 'displacement' may play an important role as well. This is the action where a volume of air is forced out of a containing system and is relevant only after evaporation has taken place.

Evaporation is generally not an important emission generation mechanism for solids at ambient temperatures, except for emission of substances by sublimation in a few cases. In situations where elevated temperatures occur, the specifics of the process can influence the temperature of the product and this again influences the partial vapour pressure of the substances in the product. These factors were found to influence, e.g. fume emissions in welding (Dennis *et al.*, 2001). Air currents (thermal convection) caused by heat from the molten materials further increase emissions. Because the temperature at the melt and the related 'vapour pressure' of the substance at that temperature will generally not be known, a proxy is proposed. This proxy is based on the differentiation between techniques (e.g. different welding techniques such as manual metal arc welding, tungsten inert gas welding, etc.) and between the materials handled (e.g. stainless steel, aluminium, different polymers). In reality this implies that generic modeling of emissions as a result of this generation mechanism is very difficult for solids heated to high temperatures.

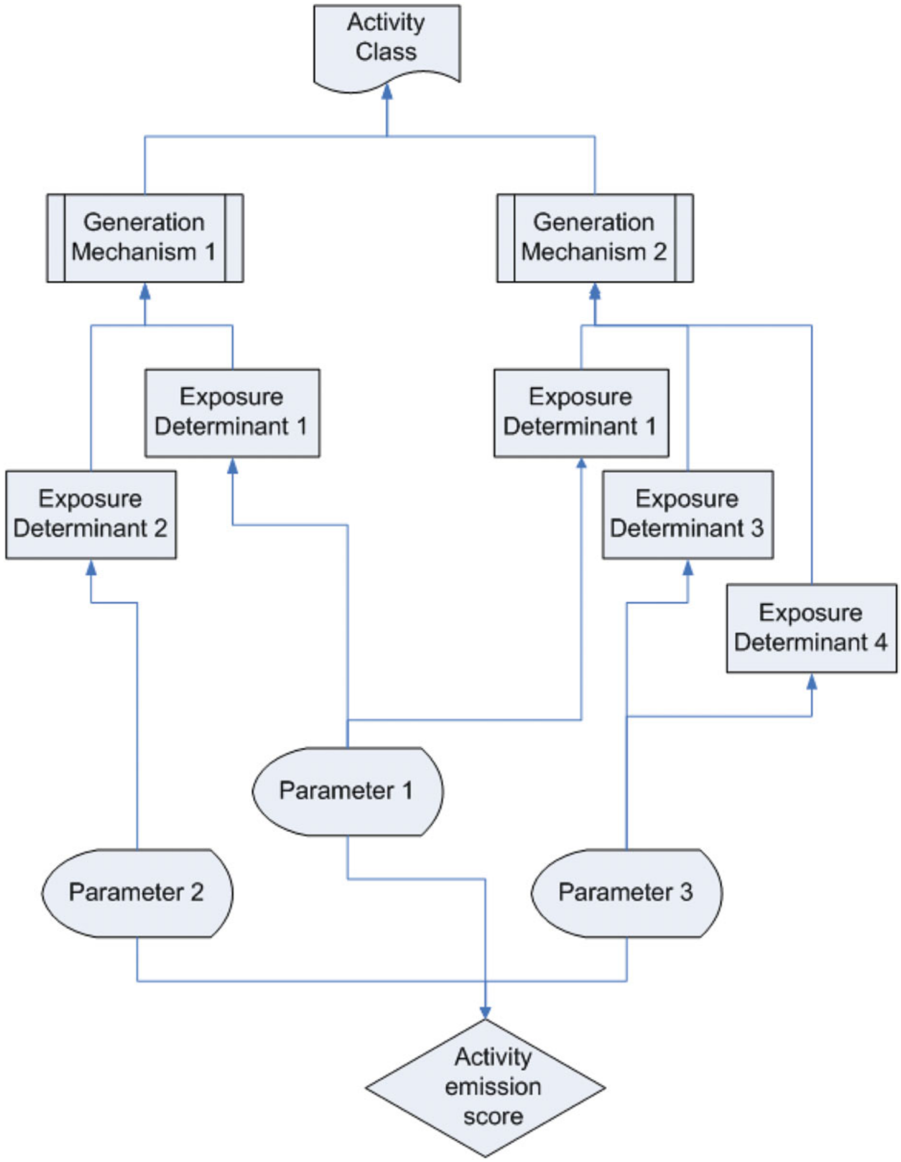

Fig. 1. System of Activity Classes, generation mechanisms, exposure determinants, parameters and activity emission scores.

Emission due to evaporation also depends on the airflow over the evaporating surface (higher airflow leads to higher emission). The relative airflow can partly be caused by the activity, e.g. for pouring of liquids. The airflow due to, e.g. the ventilation and moving objects in the area is generally not linked to the activity. Due to this mixture of influences, it was decided not to use the (relative) airflow in itself as a determinant of activity emission potential related to evaporation.

Movement

The emission generation mechanism 'movement' leads to emission because substances are 'dislodged' from a surface by this movement. This occurs because there is an energy transfer that is high enough to overcome the inertia and physical binding forces that keep substances on the surface. Inertia is the resistance of an object or a product to a change in its state of motion. Substances in an object or present at the surface of an object may be released when the

Table 2. Activity Classes, Activity Subclasses, and emission generation mechanisms

Activity class	Description	Activity Subclasses	Emission generation mechanisms	Example activities
Exposure to substances that are part of or adhere to a solid object[a]				
Fracturing and abrasion of solid objects	Activities where solid objects are broken into smaller parts or are abraded due to frictional forces.		1. Crushing 2. Impaction 3. Abrasion	Crushing concrete, Jack hammering, Pulverizing, Sawing using a circular saw, (Manual) milling, Sanding, (Cut-off) grinding of steel, Drilling, Buffing, Polishing, Chiselling, Cutting, Logging, Demolishing with wrecking ball, Wrecking, Shredding of batteries, Wire drawing, Cold rolling of metal sheets
Abrasive blasting	A surface preparation technique for removing coatings or contamination by propelling abrasive material towards the surface at high velocity. ART only considers exposure arising from the surface coatings during abrasive blasting (i.e. exposure to the abrasive material is not included)		1. Abrasion 2. Pressure difference	Grit blasting, (Ultra) high pressure blasting for stripping paint, Water cutting
Impaction on contaminated solid objects	Activities where impaction or striking of a tool on an object contaminated with powder or granules potentially results in re-suspension of that powder. For this activity class, exposure is estimated to be related to the level of contamination on the surface or the object that is impacted on.		1. Impaction	Hammering, nailing, piling, punching
Exposure to substances that are part of or adhere to a powder, granule, or pelletized material[a]				
Handling of contaminated solid objects or paste	Handling 'or transport' of surfaces, objects, or pastes that are (potentially) contaminated with powders or granules. For this activity class, exposure is estimated to the contamination on the surface, object, or paste.		1. Movement	Sorting, stacking, carrying, picking/ collecting objects, packaging, paving, wrapping, disposal of empty bags, plastering, kneading, modelling of product, bending metal tubes
Spray application of powders	Spraying activities used to intentionally disperse powders on surfaces by using a pressure difference.		1. Pressure difference 2. Impaction	Dusting crops, powder coating, spraying of concrete
Movement and agitation of powders, granules, or pelletized material	Activities where movement and agitation of powders results in disturbances of the product causing dust particles to become airborne.		1. Movement 2. Agitation	Sweeping, application of compressed air, vacuum cleaning, mixing, weighing, raking, sieving
Transfer of powders, granules, or pelletized material	Activities where a stream of powder is transferred from one reservoir (or container, vessel) to the receiving vessel. The product may either fall due to gravity from a high to a lower point (dumping of powders), be transferred horizontally (scooping of powders) or is transferred through a hose or tube with pressure (vacuum transfer).	Falling of powders, granules, or pelletized material	1. Gravitation 2. Impaction	Bagging solids, dumping solids in mixers, loading barges with minerals or cereals, scooping, scattering, filling of bottles
		Vacuum transfer of powders, granules, or pelletized material	1. Pressure difference 2. Impaction	

Table 2. *Continued*

Activity class	Description	Activity Subclasses	Emission generation mechanisms	Example activities
Compressing of powders, granules, or pelletized material	Activities where powders, granules, or pelletized material are compressed due to compaction or crushing.		1. Crushing 2. Impaction	(steam)Rolling, compacting, tabletting, granulation, pelletization
Fracturing of powders, granules, or pelletized material	Activities where powders, granules, or pelletized material are crushed and broken into smaller parts or sizes due to frictional forces (e.g. between two surfaces or objects)		1. Crushing 2. Impaction 3. Abrasion	Grinding minerals, milling cereals, very small-scale crushing, testing tablets, de-lumping (breaking up products), large-scale bulk milling
Exposure to substances that are part of or adhere to liquid products				
Spray application of liquids	Activities used to atomize liquids into droplets for dispersion on surfaces (surface spraying) or into air (space spraying). Spraying techniques may be used for dispersion of, e.g. pesticides, biocides, and paints.	Surface spraying of liquids	1. Pressure difference 2. Evaporation 3. Impaction	Spray application of paints on, e.g. ships (using High Volume Low Pressure (HVLP) or airless techniques), pest control operations (using backpack), spraying cleaning agents onto surfaces, foaming, tractor-mounted spraying
		Spraying of liquids in a space	1. Pressure difference 2. Evaporation	Spraying room deodorizers or fragrances, fogging, fly spray
Activities with open liquid surfaces and open reservoirs	Handling of a liquid product in a bath or other reservoir. The liquid may either be relatively undisturbed (e.g. manual stirring, dipping in bath) or agitated (e.g. gas bubbling, mechanical mixing in vessel).	Activities with relatively undisturbed surfaces	1. Evaporation	Dipping objects in a cleaning bath (where the presence of treated surfaces in the area is limited), immersion of objects, manual stirring of paint, tank dipping
		Activities with agitated surfaces	1. Evaporation 2. Agitation	Electroplating, bath with gas bubbling, mechanical mixing/blending of paint, aeration of waste water, boiling, shaking liquids (e.g. in chemical laboratories)
Handling of contaminated objects	Handling of solid objects that are treated or contaminated with the liquid of interest.		1. Evaporation	Heat drying tasks, evaporation from painted surface or object, maintenance of fuel pumps, coupling and decoupling of hoses or (drilling) equipment, handling of contaminated tools
Spreading of liquid products	Activities where liquid products are spread onto a surface		1. Evaporation	Painting a ceiling and walls with a roller and a brush, hand lay-up activities with styrene, pouring a liquid flooring material on a floor, cleaning of liquid spills, gluing, mopping, embalming, laminating, lubricating, sponging, screen printing, cleaning of oil residue from bulk tanks

Table 2. *Continued*

Activity class	Description	Activity Subclasses	Emission generation mechanisms	Example activities
Application of liquids in high speed processes	High energy activities with, e.g. rotating tools where liquids are added to the process (e.g. metal working fluids).		1. Movement 2. Agitation 3. Evaporation	Use of metal working fluids with, e.g. circular saws and drills, centrifuging wet items, press printing
Transfer of liquid products	Activities where a stream of liquid product is transferred from one reservoir to the next. The stream may either fall or glide from high to a lower point (falling liquids) or is transferred with pressure (pressurized transfer: e.g. bottom loading).	Bottom loading	1. Evaporation	Bottom loading of tanker at bulk terminal, under wing refuelling of aircraft, transfer of additives in tanker using bottom loading
		Falling liquids	1. Gravitation 2. Impaction 3. Evaporation	Top loading of tanker at bulk terminal (boats, rail car, or truck), filling of drums, pouring, filling of bottles, filling of paint gun, refuelling of cars, manual calibration of fuel pump, over wing refuelling of aircraft
Burning of liquids[b]	Activities where a liquid product is burned. The process of burning leads to elevated temperatures and to reactions in the liquid as well as in the vapour.		1. Burning 2. Evaporation	Burning of liquid fuel

[a]Similar Activity Classes (and Activity Subclasses) can also be developed for fibrous objects and products, e.g. ‘Handling of fibrous objects’ in which ‘Sorting of textiles’ would be an example activity. However, the present version of ART does not include exposure to fibers yet.
[b]This Activity Class is not yet included in ART. Similar Activity Classes can be developed for burning of solid objects and burning of solid powders.

object's state of motion changes (abruptly). This is relevant in handling of (contaminated) solids such as sorting or stacking.

Movement is often relevant in conjunction with agitation (see next section) in activities with a relatively high level of energy transfer. For example, a fast spinning object may lead to release of substances from its surface when the forces binding the substances to the surfaces are weaker than the effect of inertia. The amount of energy transferred is related to the changes in the movement, which in these activities mostly are directional changes. It is proposed to use a measure of relative 'change of movement' as a proxy determinant for amount of energy transferred. Such a measure can be related to, e.g. the number of rotations per minute of a drill that lead to emission of applied metal working fluids.

The main emission generation mechanism in (re)-suspension of solids to air (e.g. cleaning activities) is also associated with 'movement'. Here the emission is caused by a force that changes the state of movement of substances that were originally at rest in a pile or on a surface. The determinant of the amount of energy is again a proxy, with categories based on the combination of the 'technique' or method for producing the (re)suspension and the (re)suspended material. Examples of methods that lead to (re)suspension include the use of compressed air, brushing, and sweeping.

Agitation

Agitation as an emission generation mechanism is very similar to 'movement'. Agitation intended as a principal emission generation mechanism is the acting of motive forces on a product leading to substantial movement within the product, without necessarily a movement of the product as a whole (that is eminent in the emission generation mechanism 'movement'). The agitation may lead to (temporarily) dislodging of substances from surfaces or its parent material. It thereby increases contact with air and hence the possibility for emission. Ultrasonic vibration, shaking of liquid containers, and bubbling of gas through a liquid are all examples of agitation.

Agitation may also lead to movement of air above the product, which increases transport of dislodged aerosols further from the source into the adjacent air. The effect of an agitating force on a product not only depends on the amount of energy applied but also on the resistance of the product to movement. Therefore, a proxy determinant based on the visible effect of agitation is proposed for the amount of energy transferred. A number of categories and related examples can be used to describe the level of agitation (e.g. limited agitation, moderate agitation, and high level agitation).

Gravitation

The influence of gravitation on products results in a stream of powder or liquid that falls or flows from a higher point to a lower point. This stream interacts with air, inducing air currents in and around the stream and release of vapour, dust, or droplets from the stream. The friction due to flowing also leads to secondary emission generation mechanisms such as agitation and abrasion. It also induces impaction of the stream at the receiving surface, which again leads to interaction with air and further release of dust or droplets. Impaction is described as a separate emission generation mechanism (see below). When the product fills a container, the secondary mechanism 'displacement' is also relevant. To achieve gravitational transfer, a limited pressure may be used to force the flow of material to the point where the gravitational effect starts. However, this pressure is assumed to be too low to lead to dispersion through air (i.e. the product is transferred in a relatively dense stream). The proxy determinant of amount of energy transferred for gravitation is the falling height of the product (Cowherd *et al.*, 1989; Heitbrink *et al.*, 1990, 1992; Plinke *et al.*, 1991; Wypych *et al.*, 2005).

Crushing

Crushing is the activity where solids are broken into parts by a frictional force exerted by two or more objects. The frictional forces also lead to shear forces in the product or object contributing to the crushing effect. When the product or object is broken into parts, dust particles can be emitted into the air from the product or object or from contaminants attached to an object. The crushing action may also induce an air stream that further increases the emission. The determinant for amount of energy transferred is either the pressure (force) with which objects are forced together or a proxy for the crushing technique (e.g. impactor, jaw crusher, roll crusher, scrap shredder).

Abrasion

Abrasion is the release of substances from solids due to frictional forces. Airborne particles, including any contamination (e.g. liquids) on them can be released. The emission depends very much on the abrasive technology used. The frictional forces can be caused by another object (e.g. a grinding wheel) or by a product forcefully applied to the solid object (e.g. high pressure water jet or grit blast). The amount of energy transferred is determined by factors such as relative speed of surfaces and number of abrasive contact points between the objects (Flynn and Susi, 2003; Hamill *et al.*, 1991). It can be described pragmatically by a proxy based on the abrasive technique and a proxy based on the abraded object material. In this way, categories may be defined from limited energy transfer (e.g. manual sawing of wood), through more intensive energy transfer (e.g. belt sanding of wood) to high energy transfer (e.g. milling in a concrete wall or grit blasting).

Impaction

The impaction of solid objects or products onto (contaminated) surfaces can lead to scattering of product into droplets or dust and subsequent emission of aerosols. Such impaction can be caused by gravitation, by spray dispersion, or by forced motion of the surface (of an object) onto another object (e.g. hammering). The speed at collision influences the emission. The speed of a solid object driven into or onto another object can be known and can be used directly as a parameter. For spray applications, the speed at collision depends on the pressure difference and the distance between nozzle (point of departure) and surface (point of impact). For falling powders or liquids, the dropping height is relevant.

Burning/oxidation

Burning of products (e.g. gasoline) or solid objects (e.g. logs of wood) leads to the release of substances from the products or objects. The burning action breaks binding forces between parts or substances and the heat of burning results in a substantial air flow from the hot material, taking any light solid particles, liquids, and gases with it. Burning often results in substances being emitted that are different chemicals from those in the solid object due to the chemical reactions taking place. Further reactions take place between substances/particles and components of the air. However, burning is not always complete and it therefore often also leads to substantial emission of original components. The roasting of metal ores and the production of metal oxides by melting at very high temperatures is also considered to be a form of 'burning' in the scope of this paper.

Burning is usually the result of chemical processes releasing energy in combination with an ignition source and sufficient availability of oxygen. In some cases for burning a substance, energy needs to be largely added by a separate source, e.g. in roasting metal ores. There is no easy parameter for amount of energy transferred in this Activity Class. Therefore, it is proposed to once again use a proxy based on a combination of the technique used for burning and the material burned in the process. Both factors influence the speed and effectiveness of the burning process, e.g. the control of oxygen addition to the burning process and the temperature of the material. This in turn influences the emission of substances. For this activity, a categorization can be made in, e.g. open burning (no control of oxygen flow and flue gas at all), enclosed burning (limited control of oxygen flow and flue gases), closed controlled burning (oxygen flow and flue gas controlled) and specialized burning (e.g. engines of vehicles with high quality control of burning parameters). A categorization can be made for the material burned, e.g. solid coal-like fuels, wood, refuse, different liquid fuels, and metal ores or ingots.

Convection

Convection is the transport of mass and heat by mass motion of fluids (liquid, gas) caused by temperature differences in the fluid. Hot material expands and therefore has a lower density and moves from material with a higher density. Air above hot surfaces is also heated and therefore moves upwards. In and above heated (molten) metals, convection transports hot material to the surface from the metals and the convection of the hot air emits the material from the metal surface into the surrounding air. The temperature of the hot material and the difference in temperature with the surrounding material and air influence the emission.

DERIVATION OF ACTIVITY CLASSES AND ACTIVITY SUBCLASSES

The process of developing Activity Classes and Activity Subclasses was an iterative process. At the start, a more or less theoretical approach was followed to propose a set of Activity Classes and Activity Subclasses. The proposed Activity Classes and Activity Subclasses were then reviewed and tested by industrial partners in the project. These partners [Institute for Occupational Safety and Health of the German Social Accident Insurance (IFA), Shell, GlaxoSmithKline] all tried to fit their activities in the proposed Activity Classes and Activity Subclasses. Where the system was considered not sufficient to fit all activities in an understandable way, the partners suggested changes in the system. Based on the suggestions, changes were made. Part of these changes were made to allow better understanding by practical users in industry sectors of the Activity Classes and Activity Subclasses and to allow a better fit with already existing groupings of activities in industry sectors. The final system of Activity Classes and Activity Subclasses as presented here is therefore developed by a mix of theoretical and pragmatic arguments.

The first step in the approach was to derive Activity Classes based on differences in emission generation mechanisms and physical states because this leads to a clear structural distinction between types of activities. In principle, each combination of a separate emission generation mechanism and a separate physical state (solid, liquid) leads to a separate Activity Class. However, some emission generation mechanisms only apply to one physical state, e.g. evaporation, which is generally considered to be only relevant to liquids. Furthermore, each combination of two or more emission generation mechanisms and a separate physical state can lead to a separate Activity Class. However, several theoretically possible combinations of emission generation mechanisms are considered to be logically inconsistent. For example, the emission generation mechanisms crushing and pressure difference are unlikely to occur at the same time in one activity. Those cases will not lead to a distinction in Activity Classes.

In line with this concept, new Activity Classes may be added in the future by making new combinations of emission generation mechanisms and physical states. If necessary, new emission generation mechanisms could also be added in the future.

The determinants 'product to air interface' and 'scale' cannot easily be expressed in the same units for different activities within some of the Activity Classes. For this reason, Activity Subclasses have been defined for some Activity Classes. As a result, each Activity Subclass has one set of similar parameters that can be used to assess the activity emission potential. So, within the same general determinants, different sets of specific parameters may differentiate between two subclasses of the same Activity Class.

In the second step, a first concept of the Activity Classes system was reviewed by industrial partners. The developers asked them to fit their activities into the Activity Class system. Based on this exercise, Activity Classes or Subclasses were added if activities did not fit in the concept. As a result of this process, vacuum transfers were added and bottom loading and splash loading were distinguished. Similarly, handling contaminated objects (contaminated with liquids) was distinguished from spreading liquids and spray applications were differentiated into two subclasses: surface spraying and spraying in a space. Also, for several Activity Classes, additional categories for parameters representing scale of the process were added and for 'handling of contaminated objects' and 'impaction on contaminated objects' a category for 'handling of (or impaction on) apparently clean objects' was added. Furthermore, descriptions for several Activity Classes were improved. A part of the refinements is also described by McDonnell *et al.* (2011). The development of the Activity Classes was an iterative process which stopped when all the activities (modeled by the same exposure determinants) suggested by developers and industry could be placed in an Activity (sub) Class.

ACTIVITY EMISSION POTENTIAL, UNDERLYING PARAMETERS

Source emission is determined by energy transfer (as discussed under 'emission generation mechanism') and by factors that are related to product-to-air interface and scale. Product-to-air interface is the factor that describes the relative contact between a product and the air, while scale describes the amount of product available for emission. These two factors are not always easy to distinguish or to evaluate. Ideally, the result of their effect should be expressed in terms of amounts per unit of time, because they are used to assess emission, for example by using 'use rate' (in amount/time) for scale, while using a unitless relative factor for product to air interface.

A pragmatic solution to these problems is to use proxy parameters for scale and product to air interface separately or to use one proxy parameter or a set of proxy parameters for the combination of scale and product to air interface. Situations are then allocated to categories of these proxy parameters. The proxy parameters for scale can be different for different Activity Classes or Activity Subclasses. For activities where there is a clear 'use rate' this parameter can be used as a proxy for scale. This is possible for application of products onto surfaces, with or without spraying (Bjerre, 1989; Datar, 2003; Naidu Potana, 2005; Warren *et al.*, 2006). The application technique determines the product to air interface, which would, for example be very high for spraying with small droplet sizes, lower for spraying with high droplet sizes, and lower still for rolling and brushing. For transfer activities, 'transfer rate' is a form of 'use rate' that can be used as the parameter for scale (Heitbrink *et al.*, 1992; Plinke *et al.*, 1991; Wypych *et al.*, 2005). In these activities, product to air interface would be determined by the relative contact with air that the product has during transfer. This would be very high for splash loading or dumping of powders from bags, lower for submerged loading or transfer of powders through pipes, and very low for transfer of gases in a closed system (MRI, 1986; USEPA, 1995). A possible unit for scale in filling of containers would be the number of containers times their volume, as this determines the amount of contaminated air displaced during the activity.

For activities in which products or objects are crushed or burned, objects are abraded or solids are melted (partially), the scale may be presented by the amount per unit of time of solids, objects, or products transformed. Dennis *et al.*, (2001), for example showed that the emission of fumes in welding depended on the surface area of molten metal in the arc wire. The product to air interface in these cases is a unit-less factor that indicates how much of the product is in contact with air in these activities. This is generally a proxy that is related to the technique or equipment used. For example, the product to air interface is low for crushing in between two millstones, while for grinding in a quarry crusher the product to air interface is higher.

In several activities, there is basically a fixed amount of product (or material) during the activity, such as in dipping activities, (re)suspension of solids from surfaces into the air or activities where agitation is the main emission generation mechanism. In these cases, there is no clear 'use rate'. Also, the full amount or volume of a product is not necessarily relevant for emission because often only substances from a top layer of the product actually can be emitted. Therefore, either no practical parameter for scale can be used or a very specific parameter related to the specific activity can be used, such as 'level of agitation' for the Activity Class 'Movement and agitation of powders, granules or pelletized material'.

To conclude, as with energy transfer, the allocation of activities to categories of product-to-air-interface and scale has been based on descriptive examples because a specific parameter is often not available. Proxy parameters related to, for example, the technique and surface area can often be used instead. Table 3 shows the parameters and classes that were finally chosen for use in the tool. Exposure surveys from main occupational hygiene journals were reviewed to provide a benchmark for categorization and scoring of the activity emission potential. In the absence of sufficient 'hard' data, expert judgement was used in the process and each categorization was discussed among all members of the ART consortium as well as external experts. An example of a parameter for which the classes have been chosen more or less directly based on literature values is the surface area in 'activities with relatively undisturbed surfaces (no mist formation)'. Published exposure levels and information described by McCammon *et al.* (1991) and Von Grote *et al.* (2006) were used to conclude on a range of exposure multipliers from 0.003 to 0.2 depending on surface area in contact with the air. An example of a parameter for which it was not possible to derive a multiplier more or less directly from literature is the speed of the tools during 'application of liquids in high speed processes'. Although there is information indicating that this is an important parameter (Heitbrink *et al.*, 2000), the information from published literature does not allow quantification of the influence of this parameter. Therefore, it was decided, based on expert judgment, by the developers of ART that a multiplier of 3 for large-scale activities involving high speed movement would be used as a reasonable value for this parameter. More details on the information sources used, the available data, and the process of choosing parameters and classes for Activity Classes and other 'Modifying Factors' in ART are given by Fransman *et al.* (2011).

DISCUSSION

Hierarchical coding systems are necessary to comprehensively store and classify data according to industry, job title, and activities ('t Mannetje and Kromhout, 2003; Vinzents *et al.*, 1995). Standard coding systems for industry (e.g. ISIC) and job (e.g. ILO) are often used, but no international system has been developed for occupational activities (Gomez, 1994). The PROCs developed by ECHA are intended to reflect the general occupational exposure potential of application techniques and process types. They are part of the use descriptor system that intends 'to standardize the description of the use of substances' in the scope of REACH, thereby facilitating identification of uses, building of Exposure Scenarios, and structuring the communication on uses in the supply chain. The categorization in PROCs is driven by the amount and form of energy applied in a process, the surface of the substance available for exposure, and the level of containment and principal engineering controls to be expected (ECHA, 2010). In the Activity Class system, these drivers are also included via determinants of energy transfer, product-to-air interface, and scale. However, the categorization in PROCs was considered not yet sufficiently based on determinants of activity emission potential to be used in the ART model.

According to Rajan *et al.* (1997), 'process' is a data element in the core information on occupational

Table 3. Parameters and range of inputs for activity emission potential

Activity Class	Activity Subclass	Parameter[a]	Range of inputs[b]
Fracturing and abrasion of solid objects		Type of material	Wood, stone
		Type of handling	Several options, including, e.g. 'manual handling', 'mechanical pulverization' and 'mechanical sanding', combined with 'amount' in one parameter
		Amounts of dust/size of object	Different inputs per product type. Wood: 'very limited amount of dust' to 'large amounts of dust'. Stone: 'small size objects' to 'large amounts or large objects'. Metal: 'very limited amount of dust' to 'small amount of dust', combined with 'type of handling' in one parameter
		Level of containment of the process	'Handling that reduces contact between product and adjacent air' or 'open process'
Abrasive blasting		Surface area treated	From 'micro-abrasive blasting' to 'very large surfaces'
		Wet or dry blasting	'Wet abrasive blasting' or 'dry abrasive blasting'
		Direction of blasting	'Only downwards', 'only horizontal or downwards', 'any direction (including upwards)'
Impaction on contaminated solid objects		Level of contamination	Several options from 'impaction on apparently clean objects' to 'impaction on substantially and visibly contaminated objects'
		Force of impaction	'Normal impaction (manual or light mechanical)' or 'heavy mechanical impaction'
Handling of contaminated solid objects or paste		Level of contamination	Several options from 'handling of apparently clean objects' to 'handling of substantially and visibly contaminated objects'
		Carefulness of handling	'Careful handling', 'normal handling', or 'handling that departs from regular work procedures and involves large amounts of energy'
Spray application of powders		Type of application	'Dusting using blower' or 'powder coating'
		Direction of application	'Only downwards', 'only horizontal or downwards', 'any direction (including upwards)'
Movement and agitation of powders, granules or pelletized material		Amount of product	Several options from 'movement and agitation of <10 g' to 'movement and agitation of 1000 kg or more'
		Level of agitation	'Handling with low level of agitation', 'other handling with high level of agitation', or 'application of compressed air'
		Level of containment of the process	'Handling that reduces contact between product and adjacent air' or 'open process'
Transfer of powders, granules, or pelletized material	Falling of powders	Use rate	Several options from 'transferring <10 g min^{-1}' to 'transferring >1000 kg min^{-1}'
		Carefulness of handling	'Careful transfer' or 'routine transfer'

Table 3. *Continued*

Activity Class	Activity Subclass	Parameter[a]	Range of inputs[b]
		Drop height	'Drop height < 0.5 m' or 'drop height > 0.5 m'
		Level of containment of the process	'Handling that reduces contact between product and adjacent air' or 'open process'
	Vacuum transfer of powders	Use rate	Several options from 'transferring <10 g min^{-1}' to 'transferring >1000 kg min^{-1}'
		Level of containment of the process	'Handling that reduces contact between product and adjacent air' or 'open process'
Compressing of powders, granules, or pelletized material		Use rate	Several options from 'compressing <10 g min^{-1}' to 'compressing >1000 kg min^{-1}'
		Level of containment of the process	'Handling that reduces contact between product and adjacent air' or 'open process'
Fracturing of powders, granules, or pelletized material		Use rate	Several options from 'fracturing <10 g min^{-1}' to 'fracturing >1000 kg min^{-1}'
		Level of containment of the process	'Handling that reduces contact between product and adjacent air' or 'open process'
Spray application of liquids	Surface spraying of liquids	Use rate	From 'very low application rate (<0.03 l min^{-1})' to 'high application rate (>3 l min^{-1})'
		Direction of application	'Only downwards', 'only horizontal or downwards', 'any direction (including upwards)'
		Spray technique	'Spraying with no or low compressed air use' or 'spraying with high compressed air use'
	Spraying of liquids in a space	Scale of application	'Small-scale space spraying' or 'large-scale space spraying'
Activities with open liquid surfaces and open reservoirs	Activities with relatively undisturbed surfaces (no aerosol formation)	Open surface area	From 'open surface < 0.1 m^2' to 'open surface > 3 m^2'
	Activities with agitated surfaces	Open surface area	From 'open surface < 0.1 m^2' to 'open surface > 3 m^2'
Handling of contaminated objects		(Contaminated) surface area	From 'activities with treated/ contaminated objects (surface < 0.1 m^2)' to 'activities with treated/ contaminated objects (surface > 3 m^2)'
		Level of contamination	From 'contamination < 10% surface' to 'contamination > 90% surface'
Spreading of liquid products		Scale of application	From 'spreading of liquids at surfaces or work pieces < 0.1 m^2 h^{-1}' to 'spreading of liquids at surfaces or work pieces > 3 m^2 h^{-1}'
Application of liquids in high speed processes (e.g. rotating tools)		Scale of application	'Small-scale activities involving high speed movements' or 'large-scale activities involving high speed movements'
		Level of containment of the process	'Handling that reduces contact between product and adjacent air' or 'open process'

Table 3. *Continued*

Activity Class	Activity Subclass	Parameter[a]	Range of inputs[b]
Transfer of liquid products	Bottom loading	Use rate	From 'transfer of liquid product with flow of <0.1 l min^{-1}' to 'transfer of liquid product with flow of >1000 l/min'
	Falling liquids	Use rate	From 'transfer of liquid product with flow of <0.1 l min^{-1}' to 'transfer of liquid product with flow of >1000 l/min'
		Level of containment of the process	'Handling that reduces contact between product and adjacent air' or 'open process'
		Type of application	'Submerged loading, where the liquid dispenser remains below the fluid level' or 'splash loading, where the liquid dispenser remains at the top of the reservoir'

[a]Parameters are presented in ART in the form of questions. In some cases questions contain more than one parameter, for example in the case of 'Fracturing and abrasion of solid objects'.
[b]In some cases the input options are presented in an abbreviated form. For the full description of input ranges with associated exposure multipliers we refer to Fransman *et al.* (2011).

exposure measurements. Large exposure databases generally categorize activities or processes and determinants related to activities or processes via industry or economic activity codes, such as NACE or ISIC, and job codes (Kauffer and Vincent, 2007; Kauppinen *et al.*, 2006; Symanski and Greeson, 2002; Van Tongeren *et al.*, 2000) or via a coding system that is specific for the database or whose basis is not reported in detail (Creely *et al.*, 2007; De Vocht *et al.*, 2005; Van Rooij *et al.*, 2008). These codes are not directly related to determinants of activity emission potential and differences in exposures between groups in different categories can be caused by differences in many other factors than activity emission potential.

A workshop on a source taxonomy for consumer exposure modeling defined five so-called 'bins' of consumer exposure sources: vapour from dry sources, vapour from wet sources, particulate matter sources, combustion sources, and chemical reaction sources (Kephalopoulos *et al.*, 2006). Suggestions for modeling approaches for each 'bin' were presented, but they were not based on the same structured considerations on emission as the Activity Classes in this paper.

The exposure assessment approaches developed by Cherrie and Schneider (1999) and the Stoffenmanager (Marquart *et al.*, 2008; Tielemans *et al.*, 2008b) currently use five generic and broad classes with descriptive examples to quantify the activity emission potential.

The presented Activity Class concept facilitates a much more specific and detailed classification scheme for activity emission potential that builds on this previous work. For each Activity Class, distinct classes with tailored descriptive examples for the emission potential of an activity can be defined based on a unique set of determinants. This facilitates the use of emission-related determinants in modeling and it can thereby become an important element in the development of advanced exposure assessment models and it has been integrated in the Advanced REACH Tool project (Tielemans *et al.*, 2007).

In the process of developing the Activity Class concept, some stakeholders were asked to try to allocate their activities into the system that was already partly filled with activities by the authors of this publication. This resulted in a number of modifications, as mentioned earlier. Only three industrial partners were asked to try and allocate activities to Activity (Sub)classes. However, the three partners together had data on a wide range of exposure situations. One partner (Shell) as a petrochemical company with mostly exposure situations involving (volatile) organic substance (liquids) in production, maintenance, and logistics of petrochemicals where large use rates and amounts are common. The second partner (GlaxoSmithKline) is a pharmaceutical company with mostly situations involving solids used in rather closed systems and often relatively small amounts. The third partner (IFA) has a lot of measured exposure data and related information on a wide range of exposure situations, including solids and liquids used in all kinds or industrial sectors. Together, the three partners represent a large number of exposure situations in a large number of sectors. The fact that these three partners were able to allocate their wide ranges of activities to the Activity Class system gives substantial confidence in the usefulness of the system in practice.

The resulting set of Activity Classes and Activity Subclasses is not 'validated'. The system of Activity Classes is a categorization system and as such cannot really be validated. However, it has as a goal to enable better accounting for activity emission potential in exposure modeling and the question whether the use of the Activity Classes leads to valid exposure estimates is an appropriate question. Unfortunately, available exposure data do not allow answering this question. This would require the availability of a wide range of exposure values for different Activity (Sub)classes, where all other exposure modifiers would either be constant or at least the influence of these other exposure modifiers would be known. Such a dataset does not exist and will be very costly to gather.

The ART model itself has been calibrated. In ART, each parameter input is given a score. All scores are multiplied to calculate a total ART score. In the calibration process, the total ART scores of a large number of real exposure situations have been calibrated against measured exposure levels from the same exposure situations. This calibration process cannot directly validate the Activity Classes and the chosen values for parameters of activity emission potential. The results of the calibration (published by Schinkel *et al.*, 2011) indicate that the total ART model explains ~60% of the total variation for vapour and for dusts formed by handling solid substances or by abrasion exposure forms and only ~30% for mists. The validity of the Activity Classes and of the values allocated to parameter categories for activity emission potential cannot be concluded based on this calibration study.

The final test of the approach will be the use in practice by exposure assessors in the scope of, e.g. Chemical Safety Assessment under the REACH regulation. Feedback from this practical use can be used in the future to further improve the system.

FUNDING

Dutch Ministry of Social Affairs and Employment; the French agency for environmental and occupational health safety (Afsset); CEFIC LRI, Health and Safety Executive; SHELL; GlaxoSmithKline.

Acknowledgements—The critical appraisal and testing of the system by experts from the German IFA, GlaxoSmithKline, and Shell is gratefully acknowledged.

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