Partnership for the Assessment of Risks from Chemicals

Deliverable D6.1

Title: First report on aggregate exposure for general population and workers, and source to dose models applied to case studies

WP 6 – T6.2

Partnership for the Assessment of Risks from Chemicals

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Abstract

Human exposure to chemicals may occur from multiple sources and routes related to general and occupational environments. Moreover, throughout the lifecycle of products several sources and exposure routes are involved, making the overall exposure pathway more complex. Aggregating chemicals exposure from multiple sources and routes and investigating the fate of the chemicals from its emission sources could shed light on the contributions of the different exposure determinants and thus enrich risk assessment and inform the risk management context. The PARC activity A6.2.1 is divided into two projects: the "source-to-dose" project which aims to improve knowledge and models of chemical transfers from emission sources to exposure sources in the general environment with a focus on hotspots and indoor environments, and the "Aggregate exposure" project which aims to advance knowledge on the combination of exposures sources and routes from occupational and general environments. Thirty-six institutes from sixteen Member States joined forces to propose a more integrative risk assessment and management crossing regulatory silos in line with recent incentives from European agencies (example: EFSA ExpoAdvance project) and the European Commission (example: Chemicals Strategy for Sustainability).

This deliverable presents the first application into case studies of the proposed strategy and its roadmap developed during the first years of PARC (see deliverable AD6.3). The strategy and its implementation in Parc model network is summarized in section 2. It is based on the modelling of the contaminant transfer and migration in the different compartments, from their emission sources to the exposure sources in contact with the human body, such as indoor/outdoor air and dust, food, consumer products and articles, etc. Then, aggregation of the sources is done in summing chemical concentrations in the different exposure sources by route (ingestion, inhalation, dermal contact). Applying PBK models developed in T6.2.2 PBK model enables to aggregate routes of exposure and simulate internal concentration in the different biological matrices. Internal simulated doses are then compared with HBM data in connection with T4.1 of PARC. Another challenge is to combine exposures from the general and occupational environments to perform risk assessment from source-aggregated external exposure and to better explain internal exposures observed in HBM data for the general population and for individuals in a particular occupational sector.

Section 3 gives an overview of the first application of the strategy in prioritized case studies selected from PARC priorities: metals (cd, pb, as) exposure from dust, diet, air, soil, drinking water, playground for children and cigarette including hotspots and metal industry for adults, PFAS exposure from dust, diet, aerial deposition, consumer products, lands, including hotspots and industry; pyrethroids from diet, air, dust, veterinary and medicine products, and from agricultural activities; plasticizers from consumer products, building material, air, dust, diet and plastic product industry and waste management activities. For each case study, a deeper investigation of the available data and models was conducted and relevant ones were selected to be used in the different case studies. When needed bibliographical researches were performed for example to construct a job exposure matrix for Cadmium, develop a dedicated database to chemical concentrations in consumer products (PFAS and Cadmium as first), estimate concentrations to metals in worker places, modelize concentration to phthalates in homes, etc.

Section 4 discussed how the projects aim to support regulatory risk assessment by providing methods, tools and results to advance knowledge on the combination of the different exposure sources and routes related to general and occupational environments. The output of this activity will contribute to a better understanding of the main exposure sources and routes in general and occupational environments, in integrating the modelling of the fate of the substance from its source(s) of emission to its route(s) of exposure to support European agencies in proposing effective exposure and risk management measures. Finally, it described how such developments and results can serve in practice the European Agencies and how to organize future collaborations to increase synergy between PARC and EU agencies in developing aggregate exposure assessment.

Key Words

Aggregated exposure, human exposure, multi-source exposure, multi-route exposure, risk mitigations, occupational exposure, lifetime exposure, consumer exposure, environmental exposure

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1 Introduction

This deliverable summarizes the strategy developed under A6.2.1 to assess aggregate exposure through different sources and routes related to general and occupational environments and its application to selected case studies. This strategy was detailed in the AD6.3 “Roadmap on aggregated exposure strategy through different sources and routes related to general and occupational environments”.

In the introduction section, the scientific, societal, and regulatory questions which this work aims to answer are presented as a reminder of the scope of A6.2.1, and then the strategy developed to aggregate exposure. In section 2, the methods and tools developed for aggregate exposure are outlined. In section 3, the application to selected case studies: PFAS, metals (cadmium, chromium VI, lead), plasticizers and pyrethroids are presented.

In this deliverable and in activity A6.2.1, “exposure model” is used for models estimating exposure to one or more sources of exposure, for which an aggregation strategy is not clearly in place, i.e. diet, personal care products, air, consumer products, etc. “Aggregate model” is used for models which calculate exposure considering several sources of exposure at a time such as diet + personal care products + dust + thermal paper for bisphenols (Karrer et al. 2019) or diet + dust + veterinary drugs + medicine for pyrethroids (Vanacker, Quindroit, et al. 2020a) or that combine exposures that take place in occupational and general environments.

1.1 Regulatory, scientific and societal questions

Human exposure to chemicals may occur from multiple sources and routes related to general and occupational environments. Moreover, in general, several sources of emissions such as industries, food contact material, treated indoor surfaces, etc. are involved, making the overall system more complex.

Aggregating chemical exposure from multiple sources and routes relates to general and occupational environments in integrating the fate of the substance from its source(s) of emission to its source(s) of exposure. Aggregate exposure could shed light on the contributions of the different source-route pairs involved in exposure and thus enrich risk assessment and inform the risk management context (Bruinen de Bruin et al. 2022; ECHA 2016e; European Parliament, Council 2022b; Spankie et al. 2012). The combination of this information requires modelling based on measured data from humans and their environment (Schlüter et al. 2022).

The fundamental principles of risk assessment and management are organized at the European regulatory level. Regardless of the European Union sectoral regulations, harmonized modelling methods providing a realistic estimate of aggregate exposure and the relative contribution of exposure sources are currently lacking (European Parliament, Council 2022a, 2022c, 2022b; Lamon et al. 2024; SCCS 2019, 2021; Schlüter et al. 2022). More generally, a number of experts in the field of exposure sciences consider that the development of modelling methods for estimating human exposure to chemicals is not sufficiently promoted in the field of regulatory and academic chemical risk assessment (Fantke et al. 2022; Schlüter et al. 2022). Furthermore, the EU Chemicals Strategy for Sustainability Towards a Toxic-Free Environment from the European Commission provides incentives for harmonization and policy coordination on the level of sectorial legislations, which creates the need to further develop modelling approaches (EU Commission and Parliament 2020). Based on these considerations, the ISES Europe identified exposure modelling as one of the priority areas to an overarching European Exposure Science Strategy (Schlüter et al. 2022). In this context, the ISES Europe working group on exposure models positions itself as a facilitator to make progress in this area (Schlüter et al. 2022). ISES Europe, and in particular the working group on exposure models identified the PARC program, and subsequently the activity A6.2.1, as an opportunity to make progress in the field of exposure science at European level, both through the development of new harmonised aggregate realistic modelling methods, organised within a European tool network, but also through the development of a data hub according to the FAIR principles, recognized as a key element in developing this type of approach (Schlüter et al. 2022). This refers to the links that will be established between the present activity A6.2.1. and the tasks T4.1. and T4.2, T7.3. concerning data gaps and their organization; the other activity of T6.2: A6.2.2., A.6.2.3. & A6.2.4. for the establishment of methodological collaboration; and T8.3 for the development of the PARC network model.

EFSA also prioritized the need for further developing the methodology and recently finalized its ExpoAdvance Roadmap which aimed for developing a roadmap for future actions in order to achieve a harmonized crosscutting methodology and regulatory guidance for aggregate exposure assessments covering all relevant sources and routes of exposure to chemicals, in close cooperation with European and international partners (Lamon et al. 2024). In the corresponding report, several actions were prioritized, such as: data and model collection, development of aggregate methods, aggregate decision tree, and operational tools, PBK modelling, trainings. Developments related to part of these actions are in progress in the PARC activity A6.2.1 and in the task T6.2 "Integrative exposure and risk assessment". These developments can be used by EFSA to build upon its ExpoAdvance strategy. To be noted that the work proposed in A6.2.1 has a wider scope by focusing on occupational exposures as well.

1.2 Scope of the activity A6.2.1 and the associated projects P6.2.1.a and P6.2.1.b

The activity A6.2.1 "Aggregated exposure assessment from multiple sources and routes for general population and workers" of the task T6.2 on "Integrative exposure and risk assessment" aims to advance knowledge on the combination of exposure sources from general and occupational environments. It will help to propose a more integrative risk assessment and management crossing regulatory silos. The activity A6.2.1 is divided into two projects P6.2.1a_Y1_VITO "Source-to-dose" and P6.2.1b_Y1_ANSES "Aggregate exposure".

The "source-to-dose" project aims to improve knowledge and models of chemical transfers from emission sources to exposure sources in the general environment (Figure 1, green box). Distinction between indoor / outdoor environments, and consumer products and articles is made to propose specific modelling of the contaminant transfer and migration in the different compartments, from their emission sources to the exposure sources in contact with the human body, such as indoor/outdoor air and dust, food, consumer products, etc. **The "Aggregate exposure" project aims to advance knowledge on the combination of exposure sources within and between general and occupational environments.** It starts from chemical concentrations in the different exposure sources with which humans have contact (whose outputs of the "source-to-dose" project for the general environment) and aggregate the exposure sources by route (ingestion, inhalation, dermal contact), for both local effects and systemic effects. Exposure in the workplace is modelled from the emission sources to exposure sources in contact with humans (Figure 1, yellow box). In addition to the use of source-aggregated external exposure levels, exposures from routes will be aggregated to produce internal chemical doses, being the systemic relevant dose associated to systemic effects (Figure 1, grey box). Internal doses will be calculated using TK or PBK models or proxy like absorption factors, excretion factors, steady-states etc., developed in the A6.2.2 activity. Internal simulated doses will be compared with HBM data in connection with T4.1 of PARC. Another challenge of this project is to combine exposures from the general and occupational environments to perform risk assessment from source-aggregated external exposure and to better explain internal exposures observed in HBM data for the general population and for individuals in a particular occupational sector (Figure 1, brown sector).

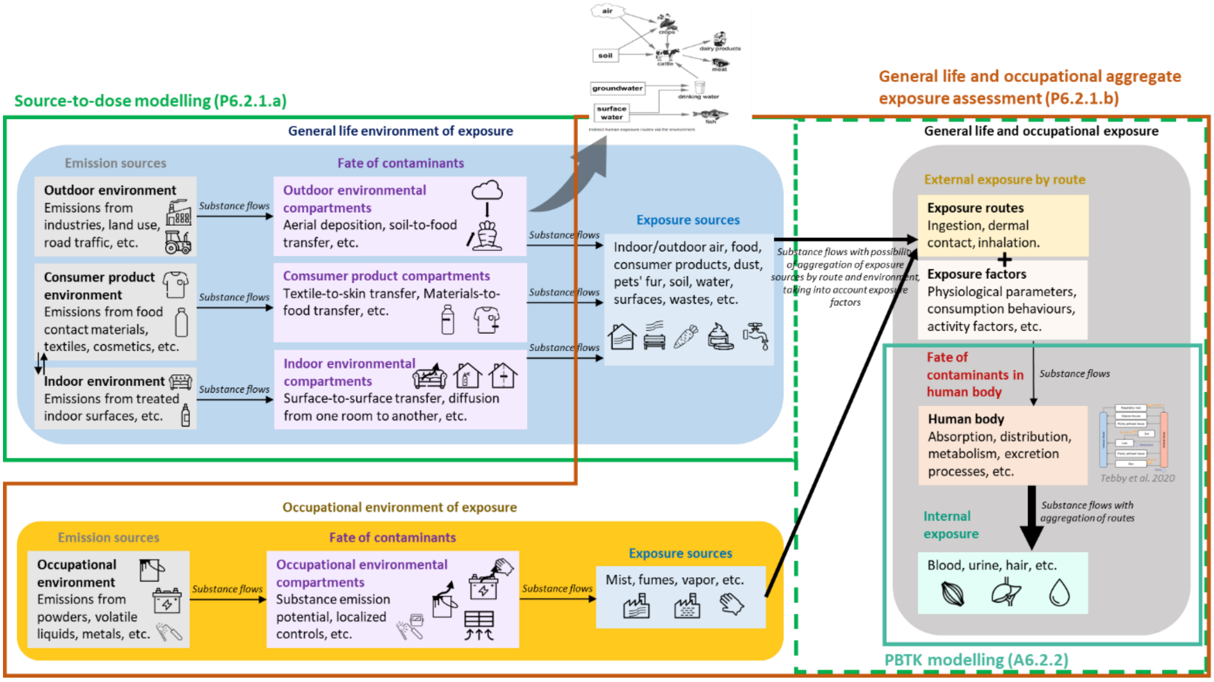


Figure 1. Aggregate modelling steps to assess exposure from multiple sources and routes from general and occupational environments in A6.2.1.

1.3 Strategy and roadmap developed under A6.2.1

To achieve the objectives of the two projects P6.2.1.a and P6.2.1.b, a roadmap of the different steps to be conducted in the activity A6.2.1 was designed. Four parts were defined (Figure 2). The part A "Inventory and review" aims to develop an **inventory of the available exposure and aggregate models, toolboxes, guidance and data to be subjected to detailed review.** The step B "Selection and connection" consists of defining appropriate criteria to select the relevant models that will be candidates for connection **in the ParcToolBox,** the **selection of relevant data** for the case studies and **the identification of recommendations** from guidance to **design the innovative approach** to perform aggregate exposure in the part C "Strategy". The last part D is the "Application to case studies" of the aggregate approach to **relevant case studies** (metals, PFAS, pyrethroids and plasticizers) selected from the defined criteria and PARC priorities. **The previous deliverable AD6.3 "Roadmap on aggregate exposure strategy through different sources and routes related to general and occupational environments" presented the Step A and B in details, this deliverable is presenting the parts C and D.** The 36 partners involved in the two projects took part in working groups presented in the Figure 3.

Connection with other tasks of PARC such as T4.1, T4.2 on collection of human biomonitoring and environmental monitoring data, T7.3 on uncertainty and T8.3 on model integration was made. The transversality between T6.2 projects was ensured by project and case study leaders and by the organization of a transversal meeting in Brussels in April 2024. For example, risk drivers of mixtures identified in the A6.2.3 Real-life mixtures project has helped to select the case study of A6.2.1. The PBTK models developed in A6.2.2 will be used in the last year of the two projects to compare modelled aggregate systemic exposure from several exposure sources and routes from this activity with HBM data.

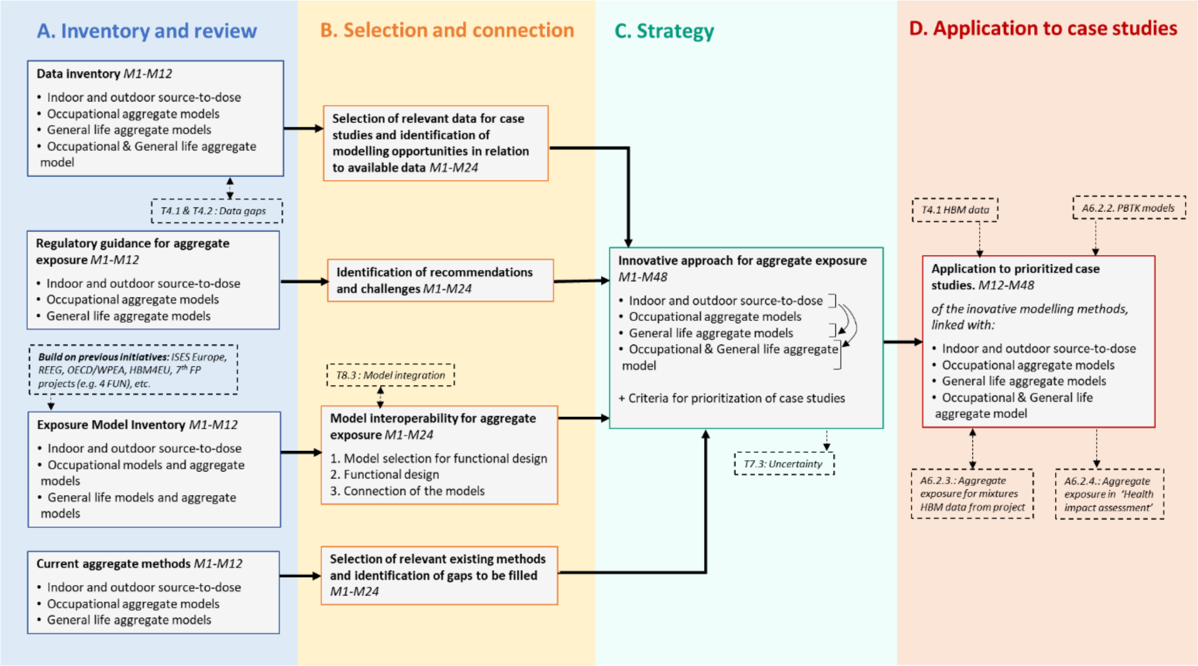


Figure 2. Roadmap proposed in A6.2.1 to aggregate exposure from different sources and living environments and to model migration and transfer from emission sources.

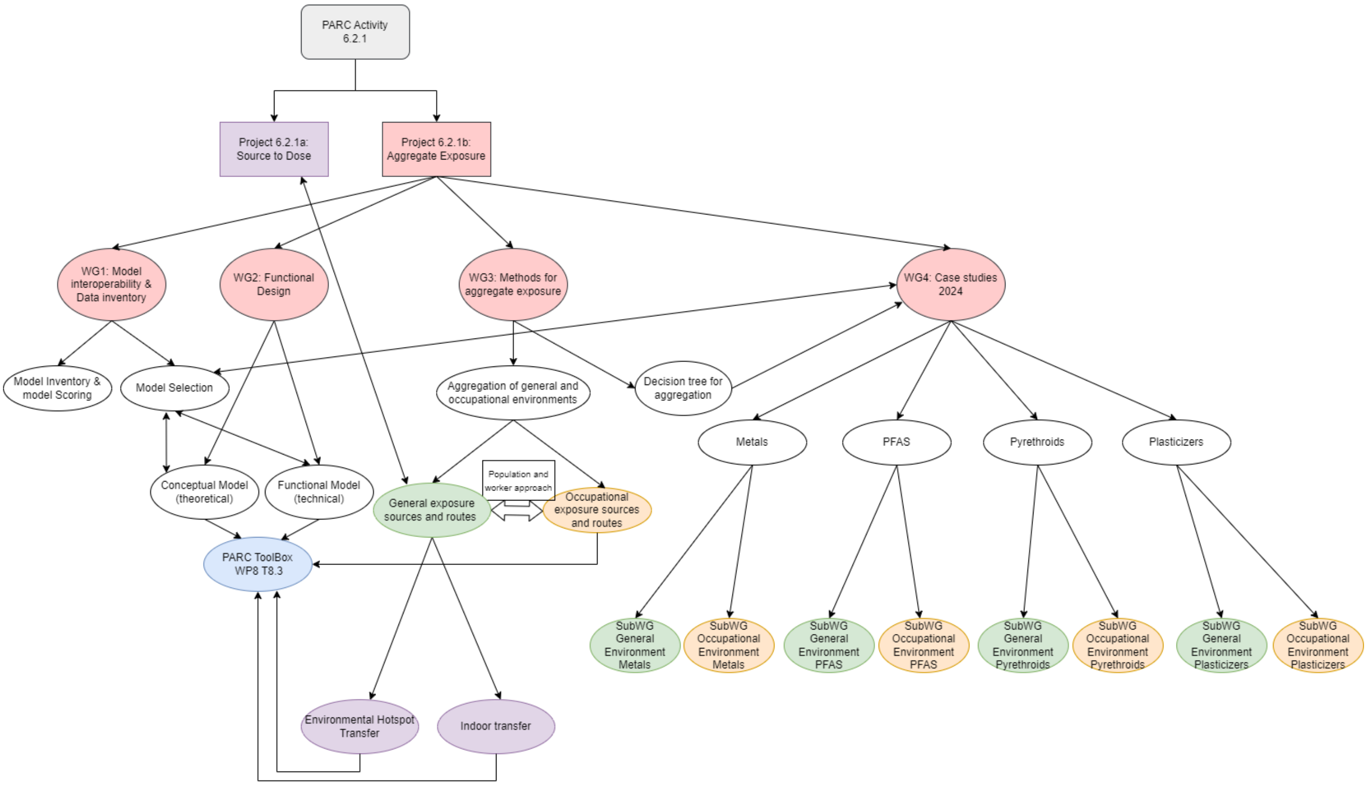


Figure 3. P6.2.1a and P6.2.1b project working groups and interactions with T8.3.

2 Methodological developments for aggregate exposure

During the first year of the two projects, we performed a review of the various European, but also international, regulations and related guidance in connection with aggregate chemical exposure assessment and source-to-dose modeling. The guidance documents from the following institutions were considered and presented into AD6.3: ECHA REACH (ECHA 2011, 2012, 2013a, 2013b, 2015, 2016e, 2016a, 2016b, 2016c, 2016d), SCCS (SCCS 2023), EMA (EMA 2025), and EFSA (EFSA 2016; EFSA, Anastassiadou, et al. 2019; EFSA, Cascio, et al. 2022; EFSA, Mancini, et al. 2022; EFSA, More, et al. 2019; EFSA Panel on Food Contact Materials, Enzymes and Processing Aids (CEP) et al. 2019; EFSA Panel on Food Contact Materials, Enzymes, Flavourings and Processing Aids (CEF) 2015). Since, guidance documents for ECHA Biocides and WHO/WHOPES were subsequently carried out. From this review, we concluded that there is a need to develop methods and tools for aggregate exposure and source-to-dose modelling. We worked collegially to propose some developments in our two P6.2.1.a and P6.2.1.b projects that were explained in AD6.3 and are summarized in this chapter.

2.1 Source-to-dose methodological developments

There are many different types of sources that can result in direct or indirect exposure to chemicals which may enter our body: 1) emissions from industrial facilities, traffic and households, etc. 2) diffuse environmental sources (e.g. historical soil contamination, water etc.), and 3) consumer products and articles used in our everyday life, (e.g. construction products, household products, cosmetics and personal care products, etc.). The variety in sources of exposure, implies also a variety in mechanisms explaining the transfer from sources to exposure media, and finally to exposure (doses).

Source-to-dose models are predictive tools designed to estimate chemical concentrations in the various exposure media mentioned above. These models address the lack of direct measurements of chemical concentrations in the environment, providing essential estimations needed before aggregating different exposure sources and routes.

While source-to-dose models mainly focus on predicting concentrations in exposure media, they differ from aggregate exposure models, which combine multiple exposure sources and routes to estimate overall exposure. However, the distinction between these models is not always clear-cut, as some source-to-dose models also include steps for calculating exposure doses.

We distinguished into two broad categories of source-to-dose models, i.e. indoor and outdoor sources, given the distinct different transfer mechanisms, and hence exposure models describing the mechanism.

2.1.1 Outdoor environment source to dose models

The concept and relevant transfer routes and exposures to chemicals from outdoor sources are shown in Figure 4.

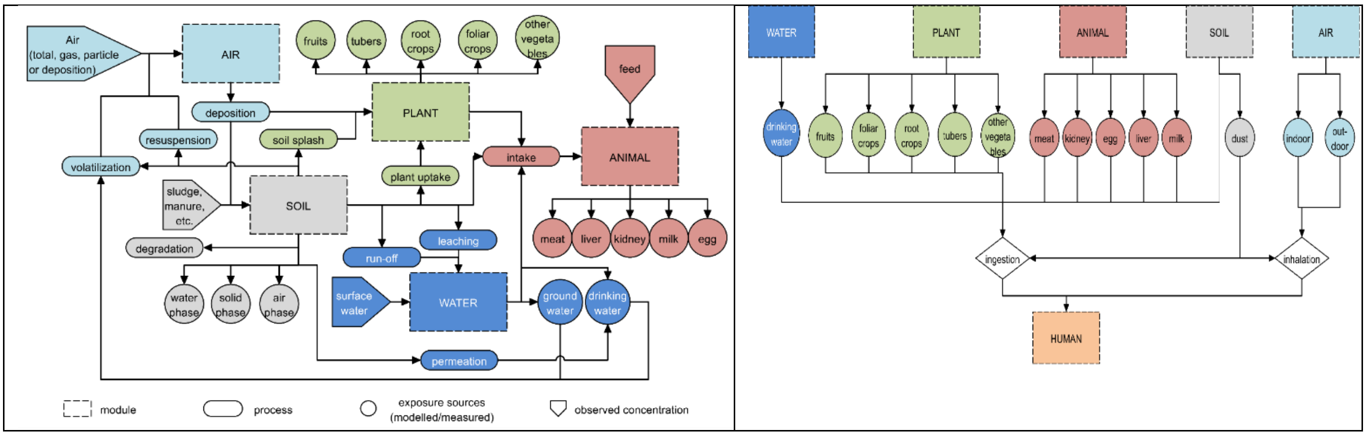


Figure 4. conceptual framework for source to dose modelling (outdoor sources). *Left part of the figure*: transfer and pathways from sources to environmental media; *right part of the figure*: from environmental media to human aggregate exposure.

There are various pathways across the source to dose exposures chain, affecting often multiple environmental media (Hoek et al. 2018). In order to visualize in a comprehensive way, we described 5 modules, one for each environmental compartment (air, soil, water) and two biological compartments (plants and animal) (see Figure 4). However, it should be noted that the modules are not standalone, and connected via pathways, presenting chemical fluxes along the source to dose chain. The first module 'AIR' starts from emission (e.g. from industry and households). Emission propagates in first instance into air concentration, leading to human exposure via inhalation; in second instance, chemicals released to air might settle down to soil (deposition), hence affecting soil quality. In addition to influx via deposition, soil can be enriched via application of manure, sludge and mineral fertilizers (module 'SOIL'). On the efflux side of the soil module, degradation, run-off, leaching to water, and uptake by plants play a role. In the module 'PLANT', influx side consists of uptake from soil, soil spash to crops, and uptake from water, while on the efflux side, harvesting crops for human consumption and animal feed are the dominant elements. Within the plant module, there is a differentiation according to crop type (root crops, foliar crops, tuber and fruit) given differences in translocation processes (and hence transfer factors) from soil, water and different impact of direct deposition on crops. In analogy, also for the module 'ANIMAL', a distinction is made in function type or animal product or tissue type. Influxes to 'ANIMAL' include feed, grazing (plants), groundwater and ingestion of soil particles. The 'WATER' module describes the role of leaching from soils, run-off, permeation (from soil across water pipes), and the use of surface water and groundwater for cattle and human drinking water purposes.

Partners of 6.2.1a outdoor project identified and mapped existing source to dose models (namely: EUSES (Vermeire et al. 1997), MerlinExpo (AFRY 2015), S-Risk (Cornelis, Standaert, and Willems 2022), Caltox (University of California 1994), Csoil (RIVM 2021), INTEGRA (Sarigiannis et al. 2014), SHEDS multimedia (US EPA et al. 2008; US EPA, Glen, et al. 2012; US EPA, Xue, et al. 2012), EN-forc (Fierens 2014; Fierens et al. 2014), ANSES cadmium balance model (Carne et al. 2021), USEtox (Holmquist et al. 2020), SMURF (Cousins 2012) and PHAGM (ATSDR 2025), including the a description of key model features: pathways accounted for (and ignored for) in the models, scope and purpose of the model, land use scenario's, model parameterization, population groups (mainly age categories), uncertainty analysis, deterministic or probabilistic models, steady state or dynamic model. More details can be found in Annex 5.5.

Whereas the main focus in P6.2.1a project was initially in the upper part, i.e. transfer and pathways from source environmental media, we noticed that in general the outdoor source to dose models include also subsequent exposure model, accounting for various exposure routes and environmental media (as depicted in the lower part of see Figure 4), hence the models cover aggregate exposure.

While the concept across the different outdoor environment source to dose exposure is in general rather similar and includes at least part of the modules and pathways as shown in in Figure 4, each model had its own specificity, included or excluded processes and modules, and model parameterization (in terms of chemicals, transfer factors and exposure factors, geographical context). As a conclusion, we could not identify a one-fits-all outdoor source to dose model. Instead, the most appropriate model is to be selected in view of the purpose and scope of the case studies (see 3.1.1).

2.1.2 Indoor environment source to dose models

The concept and relevant transfer pathways and exposures to chemicals in the indoor environment (focused on indoor air and indoor dust) are shown in Figure 5.

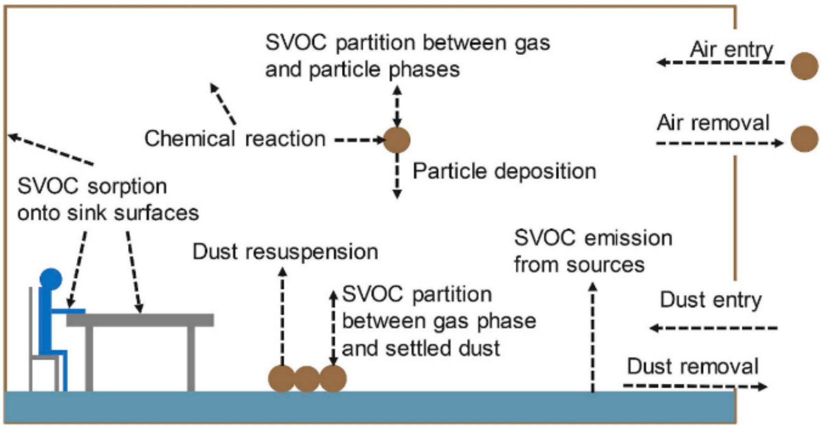


Figure 5. Conceptual framework for source to dose modelling (indoor sources). Transfer and pathways from sources to indoor media (Wei, Ramalho, and Mandin 2019).

To predict semi-volatile organic compounds (SVOC) concentrations in indoor environments (Wei, Ramalho, et al. 2019)., several mechanisms need to be considered, including: (1) the continuous emission of SVOCs from indoor sources to the gas phase; (2) the mass transfer of SVOCs among the gas phase, airborne particles, settled dust, and sink surfaces; (3) the transport of SVOCs between indoor and outdoor environments in the gas phase, airborne particles, and settled dust; (4) the gas- and particle-phase reaction of SVOCs with oxidants indoors; and (5) the deposition of airborne particles onto floor dust and other surfaces (e.g., furniture) and the resuspension of the dust into the air. Indoor environmental factors, including air temperature and humidity, air change rate and the airborne particle concentration, can influence the source-emission and mass-transfer parameters and the SVOC concentrations in the different compartments.

Partners of 6.2.1a indoor project identified and mapped existing source to dose models (namely: MOMIX, indoor SMURF and DustEx), including the description of key model features: chemical transfer and exposure pathways accounted for (and ignored for) in the models, scope and purpose of the model, model parameterization, uncertainty analysis, deterministic or probabilistic models, steady state or dynamic model. While the concept across the different indoor environment source-to-dose models is in general rather similar and includes at least part of the modules and pathways as shown in Figure 5, each model had its own specificity, in model assumption and parameterization (in terms of chemicals, transfer factors, exposure factors, and entry data format). As a conclusion, we could not identify a one-fits-all indoor source-to-dose model. Instead, the most appropriate model is to be selected in view of the purpose and scope of the case studies and whenever appropriate a synergistic/complementarity approach using multiple models was considered (see 3.1.2).

In addition to the indoor air and dust part in the indoor environment, also other than indoor air and dust related exposures may arise from indoor sources: for example: exposure to chemicals (e.g. lead) released from premise plumbing systems. This type of exposure follows specific mechanistic pathways, accounting for plumbing geometry, water consumption characteristics, lead leaching components located at a specific spot with specific leaching characteristics, i.e. all factors determining the lead concentration in drinking water at the tap. The conceptual framework for the type of indoor exposure is elaborated in the chapter on case studies (see 3.1.2).

The initial ambition was also to address in a mechanistic way the substance flows arising from other consumer articles to exposure (e.g. from textile to skin exposure, from materials to food contact or skin exposure); hereto initial discussions were held within the project team members; however due to lack of capacity and expertise within the project team, it was not realistic to develop this part of the source to dose project. Instead, it was decided to focus on the (already broad range) of above-mentioned topics in the source to dose project.

2.2 Strategy to aggregate exposures through different living environments

This section presents the main principles of the strategy we developed to aggregate exposure from multiple sources and routes within one of the living environments, either general or occupational (section 2.2.1), and to aggregate exposure from both the general and occupational living environments (section 2.2.2).

2.2.1 Aggregation of exposure sources and routes within one living environment

With the development of chemical risk assessment, plenty of models and tools have been proposed to perform risk assessment (Schlüter et al. 2022). However, in the general environment setting, most of them consider only one exposure source related to one type of living environment (general / occupational) (Schlüter et al. 2022). Some modelling approaches consider several sources, pathways or routes, of which a few propose aggregation strategies, usually on a limited number of sources, pathways and/or routes (Schlüter et al. 2022).

In the occupational setting, there is a frequent segregation of exposure models dealing with different routes of exposure (e.g., inhalation, dermal), that is rather technical or contextual in nature. This also applies to source-to-dose modeling in indoor environments, where similar assumptions and separations are common. Some routes are assumed *a priori*, sometimes incorrectly, for certain pollutants or exposure circumstances. Inhalation and dermal exposures are often considered as the only exposure routes in occupational exposure. Dermal exposure is sometimes considered as negligible when wearing gloves, protectiveness of gloves is questioned due to for example differences in work habits and behaviour. Also, there is growing evidence showing the relevant contribution of inadvertent ingestion to the total combined exposure in occupational settings (see e.g. Cherrie et al. 2006; Gorman Ng et al. 2012; Julander et al. 2020). There are currently limited possibilities for the modelling of inadvertent ingestion exposure in occupational context, with currently no exposure models available. Moreover, the exposure determinants for each occupational scenario to be considered often differ, which leads to the construction of structurally different models.

To assess aggregate exposure from multiple sources within one living environment, one way to build on current knowledge is to connect the most relevant exposure models and their output. Thus, we developed a strategy to inventory, select and connect the available exposure models. A structural analysis of the models was required to describe how the variability and the uncertainty are addressed and to identify model connection points. To connect the output exposures from the different exposure and emission source models, probabilistic approaches based on Monte-Carlo simulations were proposed to estimate aggregate exposures (Kennedy, Glass, Bokkers, et al. 2015; Kennedy, Glass, Fustinoni, et al. 2015; Kennedy, Butler Ellis, and Miller 2012; Paustenbach 2000; Safford et al. 2015; Vanacker, Tressou, et al. 2020; Zartarian et al. 2017). They allow for the simulation of random samples from dataset distributions to reconstruct sources of exposure for each individual, taking into account inter-individual variability and associated uncertainty. Second-order Monte-Carlo simulations make it possible to dissociate the uncertainty from the variability. Uncertainty of data set combination can be reduced by using stratification variables to combine the output exposure levels as explained in AD6.3. This method of source aggregation from different exposure model outputs is being implemented in the ParcToolBox (MCRA) and applied in the Cadmium case study for example, combing dietary exposure from monitoring data with consumer products exposure estimated with PACEM (Delmaar et al. 2024). More details on the strategy of model selection and connection are given in section 2.3, and example results in section 3.2.2 on Cadmium.

2.2.2 Aggregation of general and occupational environments

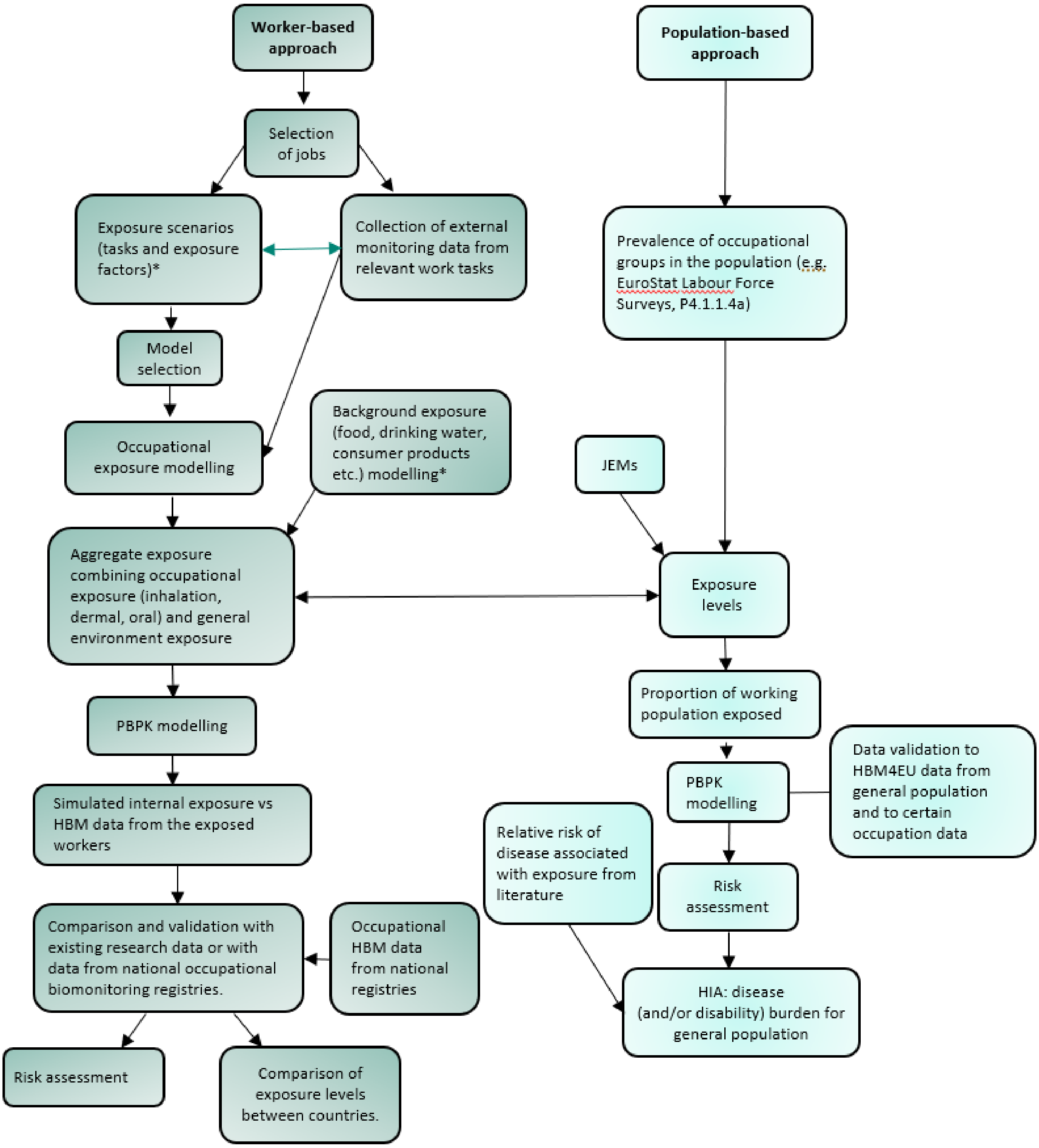
Most chemicals can be present in both general and occupational environments. For some of them, such as PFAS, heavy metals, pesticides and plasticizers, considering exposures from both types of environments, can make the difference regarding the relative significance of exposure routes, exposure pattern (e.g., chronic and/or acute exposure) and consequently, the risk. However, nowadays, exposure and risk assessment for general and occupational environments are performed independently, largely due to the specificities of occupational situations and separate regulations / responsibilities. Thus, because of this historical separation, methods, models, tools, datasets, goals and practices differ substantially between the two types of exposure. However, the respective assessment processes could converge to common methods, for instance when we come at the absorption point by oral, inhalation or dermal exposure. Moreover, with the development of biomonitoring data that reflects aggregate exposure, there is an increasing need to identify the relevant exposure sources. These exposure sources may come from the general or the occupational environment. Finally, combining exposures from both types of environments is an important challenge that will produce a better understanding of the relative contributions of each source of exposure to health effects and hence support more effective risk management measures.

Partners specialized on exposure assessment for the general population and exposure assessment for occupational population worked together to propose the testing of two approaches to aggregate exposures from occupational and general environments. These two approaches are called: worker-based approach and population-based approach and are represented in Figure 6**Erreur ! Source du renvoi introuvable.**. The two approaches were developed and started using the case studies on metals (Cd and Cr VI), PFAS, pesticides and plasticizers.

The worker-based approach starts from the worker population characterized by a particular professional activity that can lead to exposure to the targeted substance. To calculate the aggregate exposure, the exposure part coming from the general living environment is added to the occupational exposures in applying toxicokinetic models such as PBK or absorption factors. Internals dose levels are then calculated and compared to real measured human biomonitoring data. Several exposure sources and routes were considered in defined occupational scenarios and exposure estimates were aggregated with the modelled background exposure from environmental, dietary and other relevant general environment exposure sources. This approach provided information on the reliability of the modelling tools and can be used to validate modelling approaches for aggregate exposure. It will also help to identify the sources of exposure other than occupational ones to explain worker's human biomonitoring levels. However, exposure scenarios need to be defined, and detailed information on the operating conditions and typical risk management measures related to these specific scenarios are needed for modelling. Occupational exposure scenarios were chosen based on the availability of data on the task descriptions, including operational conditions and risk management measures, as well as on external exposure measurements and on biomonitoring measurements from the same scenario. Known European industrial hygienic and biomonitoring datasets were examined for the development of the scenarios. In addition, literature search was made to find possible additional exposure scenarios and to complete the data gaps from existing data. For choosing the right model to be used for exposure modelling, results from the model selection and connection process were used (Blassiau, Vernez et al. in progress, section 2.3.1). The results of external exposure scenario modelling were compared to the measured monitoring data (for example air monitoring data from breathing zone). After this step, external exposure levels from occupational environment and general environment were aggregated through PBK models to derive internal dose levels. Thus, simulated internal dose levels were then compared to the measured HBM levels in workers. For comparison either research data on occupational biomonitoring studies (for example HBM4EU chromate study) or data from national registries (e. g. Finnish biomonitoring measurements registry) were used.

The population-based approach starts from the population in the general environment and the measured exposures to the targeted substances and then identify workers in this population to account for their occupational exposures. Exposures of the different occupational groups are estimated using job-exposure matrixes (JEMs) combined with the information on the prevalence of these different occupational groups in the population. JEMs are a cross-tabulation of job titles and estimated exposures to workers carrying out these jobs during different time periods. The approach will give an estimate on the possible impact of occupational exposure to general population levels observed e.g., in biomonitoring studies. The estimates in the JEMs are based on modeling results, measurements and/or expert judgement. The JEMs are typically constructed for certain time periods and for a specific occupational classification level (e.g. ISCO-08 coding). They provide only estimates for the prevalence of exposure in an occupation and the annual mean level of exposure among the exposed workers. Thus, when possible, the application of occupational models will be used to refine currently available JEMs. The results of this exercise can be compared to the results of the project P4.1.1.4a Feasibility study, to evaluate occupational exposure in general surveys in case of Cd and Cr VI. Project P4.1.1.4a results can be also used to bring information on the prevalence of specific occupations in the general population to validate the approach, assessing the burden of the additional occupational exposure.

These two approaches answer different assessment questions. Workers-based approach assess the individual burden related to occupational exposure. It takes account the specific activity for a specific day. Combining with other exposures is also at individual level. Worker-based approach gives insights on how different routes can be combined and which issues arise from the aggregate perspective. The population-based approach assesses the burden related to occupational exposure in the entire population. JEMs are used as in general population cohorts' occupational exposure is typically not covered. This approach results in an average occupational exposure and prevalence for certain workers. These results can then be used for a population burden impact assessment. Combining with other non-occupational exposures is at population level.



*Decision of relevant sources and routes

Figure 6. Schematic representation of the approaches to aggregate exposures from general and occupational Optional passage through a decision tree. JEM: job-exposure matrixes. PBPK: Physiologically Based Pharmacokinetic. HIA: Health Impact Assessment. HBM: Human Biomonitoring.

2.2.3 Selecting only relevant sources and routes for aggregation: general approach

To understand the total exposure of a human population to a chemical, it is necessary to aggregate exposures from all relevant sources and routes. The sources and routes that contribute most to exposure should be identified for informed preventive-decisions, allowing for targeted preventive actions or decisions, prioritizing the highest risks. This is currently based on assessing the exposure corresponding to each route and source of exposure independently (i.e. each pathway of exposure), using specific models. The relative contributions of each route and source are then compared to determine which are relevant to keep in the assessment of overall exposure. Existing approaches for decision-making about exposure aggregation are scarce and remain mostly qualitative, or at the methodological level to guide users in suggesting calculations or expert judgement. Developing a quantitative and data-driven tool for guiding decision on aggregation is therefore necessary. Figure 7 is an example of what such a decision-making flowchart might look like.

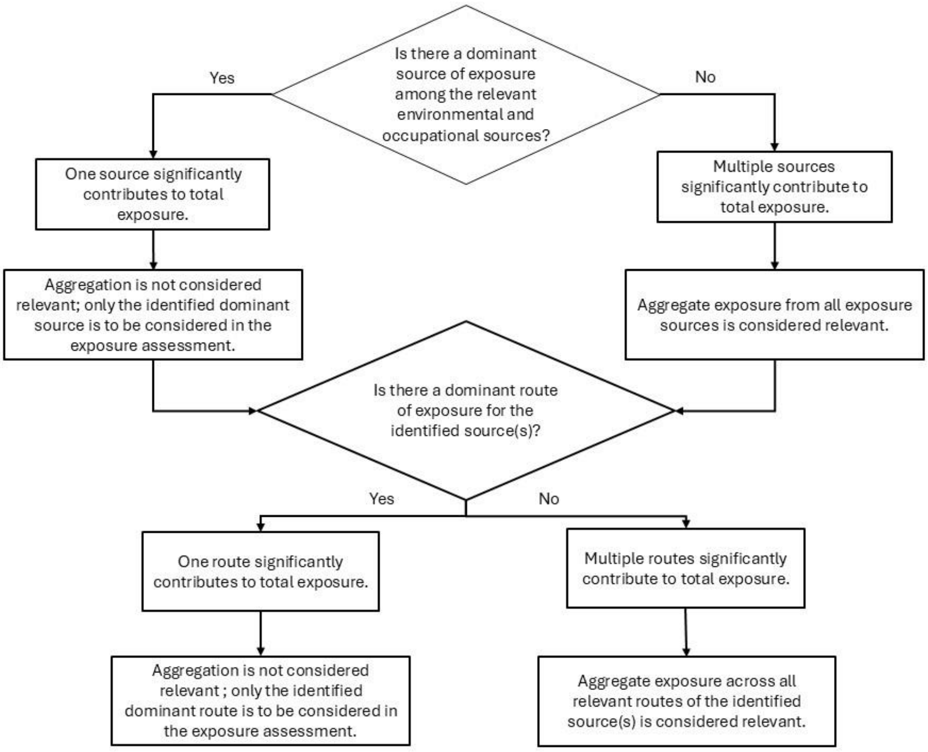


Figure 7. Generic decision-making flowchart for identifying the relevance of aggregate exposure.

2.2.3.1 Proof of concept on source selection to aggregate chemical exposures from general and occupational environments (Unisanté)

The development of a quantitative decision tree to identify the relevant sources, related to exposure situations, in a context of aggregate exposure is explored and illustrated in the case of joint inhalation exposure to a chemical in a consumer product, through domestic use of hairspray, and exposure at the workplace involving surface spraying such as spray application of paints. The exposure models ART (for workers) and ConsExpo (for the general population) were used to generate a wide range of realistic exposure scenarios. The dominance of one source over another depends on the exposure conditions within each source which are analyzed using pairwise random comparisons. For this case study, the decision tree was built using the three exposure determinants having the most influence on the aggregation decision (Figure 8).

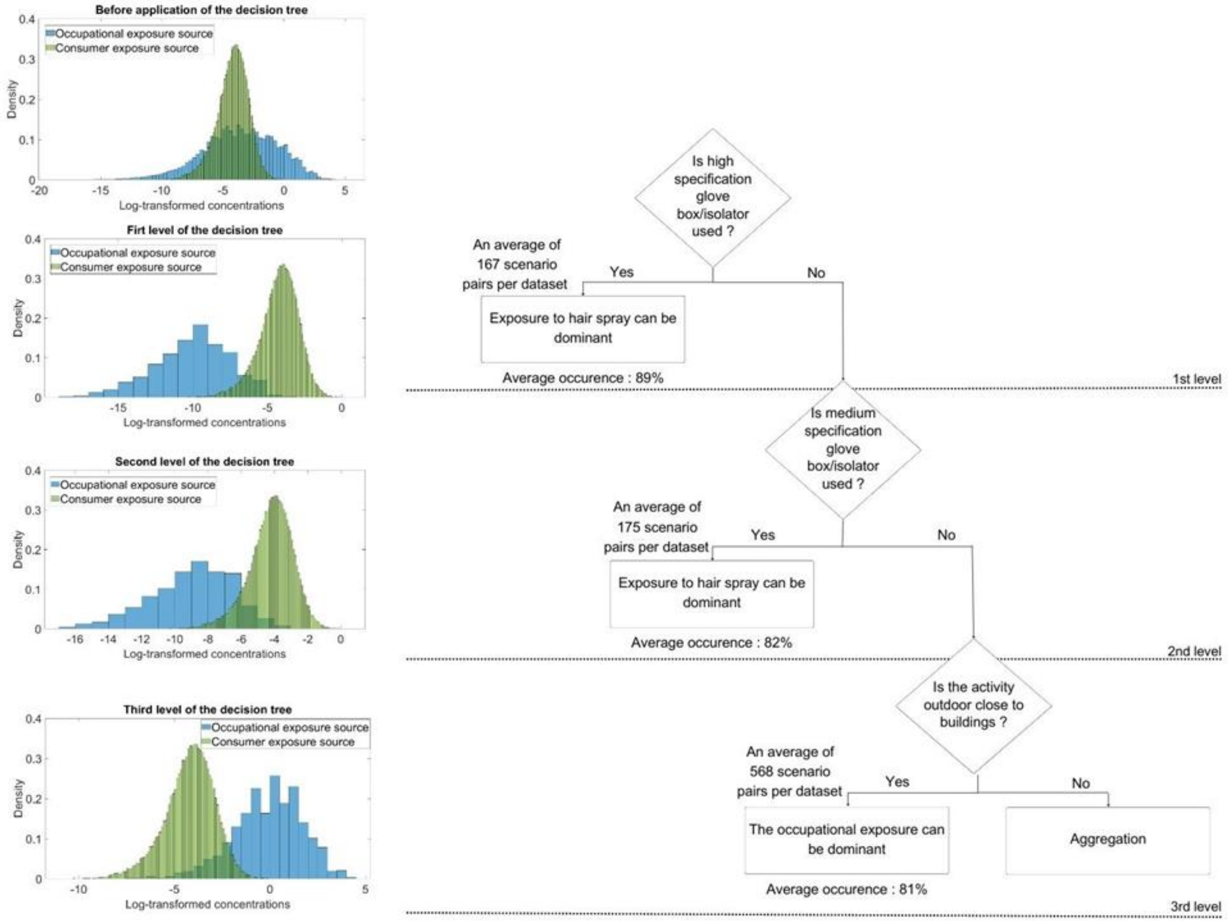


Figure 8. Example of decision-making flowchart for aggregating exposure sources and distributions of chemical concentrations in the air for hairspray and surface spraying exposure.

The main findings indicate that the use of high or medium specification glove boxes are highly effective in reducing occupational exposure. When these glove boxes are used, hair spray exposure will be the dominant source in 89% and 82% of cases, for high and medium specifications respectively. A spraying activity with surface liquids performed outdoors (close to buildings) shows a significant trend towards occupational exposure dominance in 81% of cases. Using these three criteria, it was possible to build a three-layer quantitative decision tree, allowing a user to decide quickly whether aggregation was relevant or not before performing any calculations. This proof of concept demonstrated the feasibility of developing a tool to aid decision making on the exposure aggregation and prioritization of exposure sources, thereby aiding authorities and practitioners in making informed decisions for public health protection. The comparison of exposure sources causing exposure through different routes, and the comparison of exposure routes across the same exposure source, as well as optimization of the decision-tree construction will be explored in 2025. A scientific paper on the proof of concept of this approach will be submitted early 2025 (Chettou et al., in preparation).

2.3 Model selection and connection

2.3.1 Model selection strategy for occupational and general environment

Combining the knowledge accumulated on the different parts of the exposure environment requires a good understanding of the models that already exist, in order to be able to select the best ones for reconstructing the full landscape and if necessary, make improvements to the existing models or create new models to fill in the gaps.

Understanding, evaluating, enhancing the compatibility of models, identifying gaps, adapting to regulatory needs and standardizing modelling practices between the various sources of exposure and the general and occupational environments are all relevant objectives for achieving this integration. All these issues have been included by the ISES Europe working group on exposure models in the European Exposure Science Strategy (Schlüter et al. 2022), and correspond to sub-objectives of the strategic objectives: 'Improvement of existing models and tools', 'Support for understudied research fields', 'Improvement of model use', and 'Regulatory requirements for exposure modelling'.

A6.2.1 experts in the fields of exposure modelling and data exposure propose a contribution to these strategic objectives in response to the challenge of integrated exposure. First, an update of the inventory carried out by ISES Europe was performed, in order to draw up a landscape of existing models, identify gaps and select the ones to be used for further aggregate exposure assessment, i.e. multiple sources and routes. Then, a model scoring method was set up and tested on the inventory. The scoring grid was made up of three main categories of evaluation criteria: methodology, scope and efficiency, and usability of the model. Finally, a description and selection strategy was proposed to meet the need of model understanding, compatibility and standardization in order to achieve aggregate exposure. A structured methodology was used to identify, evaluate, and select chemical exposure models for aggregate exposure assessments. A comprehensive inventory of over 200 models was compiled from various expert sources. Each model was scored using a grid of nine criteria across three categories: methodology, scope and efficiency, and usability. Evaluations were conducted by expert reviewers through a blind review process. A decision algorithm (Figure 9) was then applied to select the most suitable models based on their validity, data compatibility, and adequacy for specific substances, exposure routes, and European regions, optimizing model use in regulatory and scientific contexts. As a result of this selection strategy, the most common models selected are:: MCRA (van der Voet et al. 2015), EFSA PRIMo rev 3.1 (EFSA et al. 2018), RSExpo (Vanacker, Tressou, et al. 2020), ConsExpo (Delmaar and Schuur 2017), Pacem (Christiaan Delmaar et al. 2024), Residential SOPs (US EPA 2012), Merlin-Expo tool (AFRY 2015), Modul'ers (Bonnard 2013), Stoffenmanager (Marquart et al. 2008), Browse model/Bream2 (Butler Ellis et al. 2017), Riskofderm (Van Hemmen et al. 2003), IH-MOD (AIHA 2019a), TREXMO (Savic et al. 2016), EASY-TRA (Jansen-Systems 2010), SVOC-PM-DUST (Wei et al. 2017; Wei, Mandin, et al. 2019), OPEX (EFSA 2022), MEASE (OBRC 2018), DustEx (Allott, Kelly, and Nicholas Hewitt 1994), S-Risk (Cornelis et al. 2022), Swimodel (US EPA 2003), ART (McNally et al. 2014), dART (Goede et al. 2019), IH-SkinPerm (AIHA 2019b).

A scientific paper is in preparation.

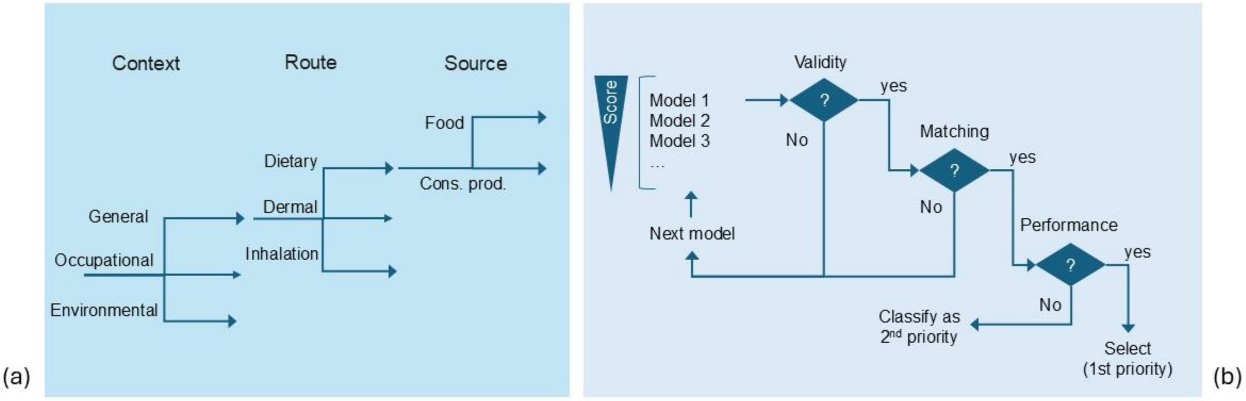


Figure 9. Algorithm for model selection. (a) selection of the model subgroup appropriate to the context, route and source considered (b) ranking of the possible models within a subgroup.

2.3.2 Model tutorials

Training sessions were organized by the collaborators who are proficient in the modeling tools considered the most commonly used for modeling. Unisanté organized two training sessions: one for the use of TREXMO (Savic et al. 2016) for modeling inhalation exposure, and the other for the use of RiskofDerm (Van Hemmen et al. 2003) for modeling dermal exposure. TNO organized one training session for the use of ART (McNally et al. 2014) for modeling occupational exposure through inhalation. WR-BIOM organized one training session for the use of MCRA (van der Voet et al. 2015) for modeling dietary exposure. RIVM organized one training session for the use of Pacem (Christiaan Delmaar et al. 2024) for modeling aggregate exposure from the use of consumer products. BPI organized one training session for the use of OPEX (EFSA 2022) for modeling non-dietary exposure to pesticides for operators, workers, residents, and bystanders. VITO gave a demonstration of the S-Risk model, a model focused on the assessment of soil related exposure assessment (integrating all soil related aspects, see 2.1.1). Finally, Anses organized one training session on the principles embedded in RSExpo (Vanacker, Tressou, et al. 2020) for modelling aggregate exposure in the general environment. Further training sessions will be organized in the future for the other selected models.

2.3.3 Functional design for model connection

The PARC model network[1] (PARC T8.3) is a digital ecosystem designed to provide access to modelling tools and (through these tools) to workflows, facilitating integrative risk assessments of chemical exposures. Its goal is to support harmonized, scalable and cross-sector risk assessments in both scientific and regulatory contexts, aligning with international (regulatory) requirements and methodological advances.

Numerous exposure models and tools are available in the CRA domain (see Section 2.3.1). However, these models commonly focus on specific sources and exposure. Additionally, PBK models can be used to aggregate exposures at an internal level. As a result, achieving practical aggregate exposure estimation requires integration of multiple models in a unified assessment. A major challenge in this process is the lack of standardized approaches, data harmonization, and interoperability among tools.

To address these gaps, **the PARC model network is developing an interconnected system of (interoperable) modeling tools and data resources**. This network will **facilitate** seamless integration within **workflows for aggregate exposure assessment**. Beyond aggregate exposure assessment, several other activities are in progress to support projects within T6.2, including: a standard for FAIR PBK models (T6.2.2), a workflow for (mixture) risk assessment based on HBM data (T6.2.3), and a workflow for environmental burden of disease assessments using (aggregate) exposure estimates or HBM data (T6.2.4). Over time, these standards and workflows aim to interconnect activities across the various projects, fostering a more integrated approach to risk assessment.

2.3.3.1 Main requirements

At an early stage of the project, the following key requirements were established for the aggregate exposure assessment workflows:

- **User-friendly & transparent**: the workflow should be easy to use, transparent, and support harmonized analyses at the European level.
- **Comprehensive exposure assessments**: the workflow should facilitate the assessment of aggregate exposure assessment from all potential sources of exposure (e.g. diet, dust, air, soil) and exposure routes (oral, dermal, inhalation) in general life scenarios, with the potential for future extension to occupational settings.
- **Flexible exposure estimate types**: the workflow should accommodate different types of exposure estimates, including a single point estimate, specific percentile values of exposure distributions, and full distribution estimates.

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[1] https://www.parc-models.eu/

- **Exposure estimates as data**: it should support linking exposure estimates obtained as outputs from external exposure modelling tools as input (data) for aggregate and internal exposure assessment using a harmonized data format.
- **Source-specific modeling**: dedicated modules, linking modeling tools, should be incorporated for estimating external exposures for specific sources and routes.
- **Combining output of multiple models**: the workflow should include strategies for combining the output of the different modeling tools in an aggregate assessment (e.g. matching by a unique identifier for each individual, random matching of individuals within strata, or random matching of individuals).
- **Tiered kinetic modeling**: it should incorporate tiered approaches for integrating external exposures at an internal level, ranging from basic absorption factors and kinetic conversion factors to advanced PBK models
- **Alignment with FAIR PBK standards**: the use of PBK models in the workflow should be in accordance with the PARC FAIR PBK standard.
- **Uncertainty assessment framework**: a structured approach to uncertainty assessment, including propagation of uncertainties through the different modeling steps in the workflow. This should align with regulatory guidance (e.g. EFSA) and / or concepts developed in PARC T6.2 and PARC T7.3.
- **Connectivity with other workflows**: the workflow should link to other components of the PARC model network, particularly downstream risk assessments, environmental burden of disease assessments, and HBM data for model validation and calibration.

2.3.3.2 Key design choices

Internal exposure estimation in a central platform

To support aggregate exposure assessment, a network of interoperable modelling tools is being developed. The MCRA web platform has been chosen as a central node in this network, linking the modelling tools and / or their outputs. This selection was based on a number of key factors:

- MCRA incorporates EFSA's methodology for probabilistic dietary (cumulative) exposure and risk assessment, which closely aligns with the methodology of T6.2.1. The platform contains a vast collection of food consumption surveys from EU countries, supporting both retrospective and prospective cumulative risk assessment of pesticides by member states (van Klaveren et al. 2024). MCRA enables standardized assessments through predefined standard (regulatory) actions (Engel et al. 2024; Kruisselbrink et al. 2023)
- As a result of the EuroMix project, MCRA already contained basic functionality for aggregate exposure assessment, meeting several of the main requirements listed above (van der Voet et al. 2020).
- Within PARC, the MCRA platform is and has been significantly extended to support additional T6.2 workflows. It therefore contains key functionality for analysis of (individual-level) HBM data using the PARC HBM data format, the use of FAIR PBK models, (mixture) risk assessment and environmental burden of disease assessment.

User interface

The MCRA web platform will feature an intuitive user interface, enabling users to setup their aggregate exposure assessment. Key functionalities include:

- **Defining the scope:** specification of population groups, substances, target levels (systemic internal exposure or internal concentration in a specific biological matrix), exposure sources and exposure routes.
- **Configuring the external exposures:** for each exposure source and route, users can choose whether external exposure estimates will be provided as input data or generated within the main workflow **through modelling steps.**
- **Configuring internal exposure estimates:** settings will be available to match outputs from different external exposure estimates, in order to aggregate them together at an internal level. Depending on the chosen target level, users can: provide absorption factors as data (for systemic exposure estimation), supply kinetic conversion factors (for internal concentration estimation), or use a PBK model by uploading a FAIR PBK model (for internal concentration estimation). The interface allows users to define how the PBK model is applied in the assessment exactly, i.e. specify the exposure events and the period for which the PBK simulation is conducted.

Modular structure and scalability

The workflow is designed to combine (outputs of) one or multiple external exposure assessment modeling tools and, optionally, one of more PBK models. This is a general characteristic of workflows in the PARC model network. Since the modeling tools have been developed in different contexts – each with its own development team, development process and / or governance structure – they are treated as individual nodes within a network of models. To facilitate integration, the PARC model network is structured modularly where each module represents a (collection of) nodes for a specific modeling activity. Modules can be combined in various configurations to create specific workflows. MCRA also adopts a modular structure which will be aligned with that of the PARC model network. The modular structure / conceptual framework that is in view for aggregate exposure assessment workflows is shown in Figure 10. The following key modules are in view:

- **External exposure modules:** multiple external exposure modules are envisioned that estimate external exposures from different routes and/or sources. Some of these modules may be directly implemented within MCRA while others may make use of another modelling tool which is automatically or manually linked to MCRA, see below.
- **Internal (aggregate) exposures**: this module processes external exposure outputs to derive (aggregate) internal exposure estimates. These internal exposure estimates may be either systemic internal exposures, or internal exposures obtained from using a kinetic conversion model (see toxicokinetic modules). It includes functionalities for matching exposure estimates across sources in terms of the observations considered and the exposure units. For matching of observations the probabilistic strategy from A6.2.1 is followed.
- **Toxicokinetic modules:** modules for deriving internal exposure estimates from external exposures. Three types of models are supported, namely absorption factors, kinetic conversion factors or PBK modes. When absorption factors are used, systematic exposures are calculated in the internal exposures module. Otherwise internal concentrations at a specific internal target (biological matrix) are derived. These follow from either a set of kinetic conversion factors or PBK models.

The conceptual framework in Figure 10 is a subset of the overarching conceptual framework of the PARC model network (D8.6[2]). Integrating the aggregate exposure workflow in the overarching modular structure of the PARC model network ensures connectivity with other workflows. A key planned connection is with HBM data which will enable validation of modelled internal exposures.

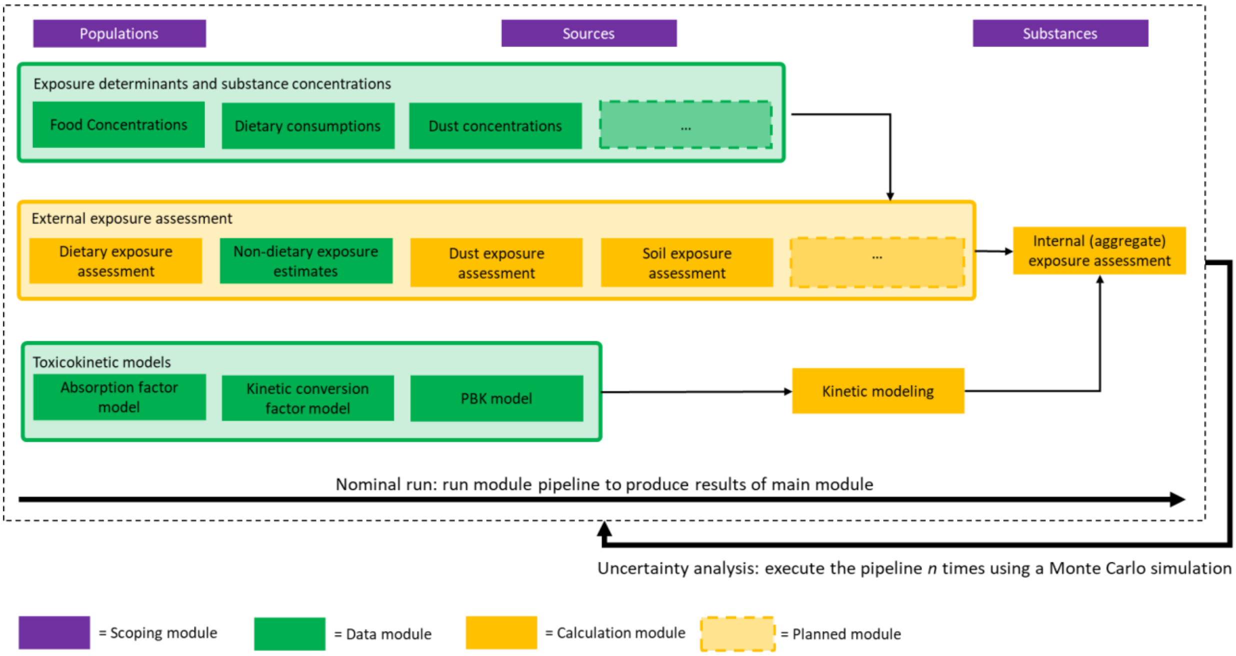

Figure 10. The conceptual framework for linking models in aggregate exposure assessment workflows. It features a network of linked data modules (green boxes) and calculation modules (yellow, representing modelling tools). The purple modules are generic scoping

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[2] D8.6 First report on the development and validation of the integrative models

models to define the population, sources, and substances in scope. This conceptual framework is also adopted in the MCRA-based workflow presented here.

Model integration: technical and conceptual requirements

The workflow integrates two types of models, namely external exposure estimation models and PBK models. For PBK model integration, the workflow adheres to the FAIR PBK standard that is being developed in PARC. This ensures that any PBK model adopting this standard can be directly “plugged” into the workflow without additional customization. While similar direct access to external exposure models is desirable, integration feasibility depends on conceptual and technical compatibility and developer support. Therefore, two integration methods are envisioned:

- **Manual workflow**: users export the output of an external exposure modelling tool in a harmonized format before manually importing it into MCRA via a dedicated module. This is visualized by the Non-dietary exposure estimates module in Figure 10.
- **Automatic workflow**: models are either embedded in MCRA or linked via APIs for seamless data exchange. Dedicated modules are available in MCRA for each exposure source that is integrated this way, e.g. dust exposure assessment or soil exposure assessment in Figure 10.

Successful model integration requires both conceptual and technical interoperability between tools and data. To guide the design of the workflow for aggregate exposure assessment, a conceptual framework and harmonized vocabulary was developed for aggregate exposure assessment [https://github.com/eu-parc/aggregate-exposure-modelling]. The conceptual framework is used to relate models to each other in the context of an assessment, and also to establish harmonized data and modelling standards.

Based on the already existing data format for non-dietary exposures developed in the ACROPOLIS and EuroMix project and implemented in MCRA, a generic data format for storing external exposure estimates was proposed[3]. In addition, specific data formats for exposure determinants and concentrations for different sources of exposure were developed (e.g., for dust and soil exposure). Later, this format may also be adopted in a broader context, based on the work in WP7 on FAIR data. Besides embracing data standards, the workflows also adopt the FAIR PBK standard (that uses the PBK ontology, currently under development in T7.2) as exchange standard for linking PBK models.

Uncertainty analysis

As shown in Figure 10, the assessments of the workflows are multi-modular, and within each module, modelling steps are performed and data are used with various sources and degrees of uncertainty. The modular framework enables quantification of uncertainty of workflows by including an outer (Monte Carlo) uncertainty loop. Instead of running a chain of linked modules once, each workflow is run for a number of times in which each module can be run in a bootstrap-mode, for instance resampling data or rerunning the models with parametrically bootstrapped parameters. In this way, uncertainty within the modules is propagated to the overall outcomes, enabling estimation of the uncertainty bounds of the quantified uncertainties of the internal (aggregate) exposure estimates.

Main output:

- Internal (aggregate) exposure distribution of the population under consideration.
- Estimates of the contributions of the different sources and/or routes to the internal exposure estimates.
- For multi-substance assessments: exposures by substance (and also by substance and source and/or route), cumulative exposure distribution (optional, depending on data inputs), substance contributions to the cumulative exposure (and substance, source and/or route contributions to the cumulative exposure).

Secondary output:

- Insight in the combined external exposure distribution of the matched/aligned external exposure estimates from the different models

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[3] https://mcra.rivm.nl/documentation/10.1.4/modules/exposure-modules/non-dietary-exposures/non-dietary-exposures-data-formats.html#non-dietary-exposures-data-formats

- Insight in the kinetic conversion. In case of the use of PBK models, the internal exposure time-series from simulations of external (daily) exposures, e.g., for selected high-exposure individuals.

Development approach

It is not feasible nor desirable to link all external exposure assessment modelling tools in the workflow. The general strategy adopted in T8.3 for building the model network is to adopt a top-down, bottom-up approach Here, the bottom-up approach involves "rapid prototyping" and implementation of practical (initial versions of) links between models based on the needs of specific (T6.2.1) case studies. The initial focus will be on general life assessments, but future developments will expand its capabilities to occupational exposure and possibly source-to-dose modelling as well. In parallel, and based on insights from the bottom-up development approach, harmonized (top-down) standards for data and models are being developed. One example is the FAIR PBK standard, which is being developed in PARC to facilitate the seamless integration and reuse of PBK models in aggregate exposure modeling workflows. Such a standard is essential for scalable implementation of aggregate exposure modelling workflows. This approach enables evolution of a continuously growing network (bottom-up) with increased standardisation and harmonisation (top-down).

2.3.3.3 First prototype

Figure 11 illustrates the initial prototype of the workflow for internal (aggregate) exposure assessment, further detailed in AD8.4[4] and D8.6[5]. It showcases the main user interface in MCRA, which enables users to select the exposure sources, routes, and internal target of the assessment. Based on the chosen exposure sources, different sub-modules are connected. Within the internal exposure module, external exposure estimates from the selected sources and routes are aligned and aggregated using, in this example, a PBK model.

The example shown in Figure 11 concerns an artificial assessment for PFOA. It combines dermal exposure estimates from consumer products obtained from PACEM, dietary exposures modeled in MCRA, and dust exposure estimates generated by the RSExpo model. These external exposures are linked to a FAIR PBK implementation of a PFAS PBK model, based on the models of Westerhout et al. 2024 and Husøy et al. 2023, to estimate the steady-state concentration at an internal level.

In this example, the consumer product exposure estimates were exported from PACEM and uploaded via the Non-dietary exposure estimates module using the harmonized data format. The RSExpo model for dust exposures was reimplemented within MCRA, making it directly accessible from the workflow. Due to the design of RSExpo – including its limited availability (only in French) and its limited options for interoperability in the current implementation within an RShiny application - embedding or otherwise linking the tool to MCRA was not feasible, necessitating reimplementation within the platform. The FAIR PBK model for PFOA, was directly plugged in the workflow by uploading it via the user interface.

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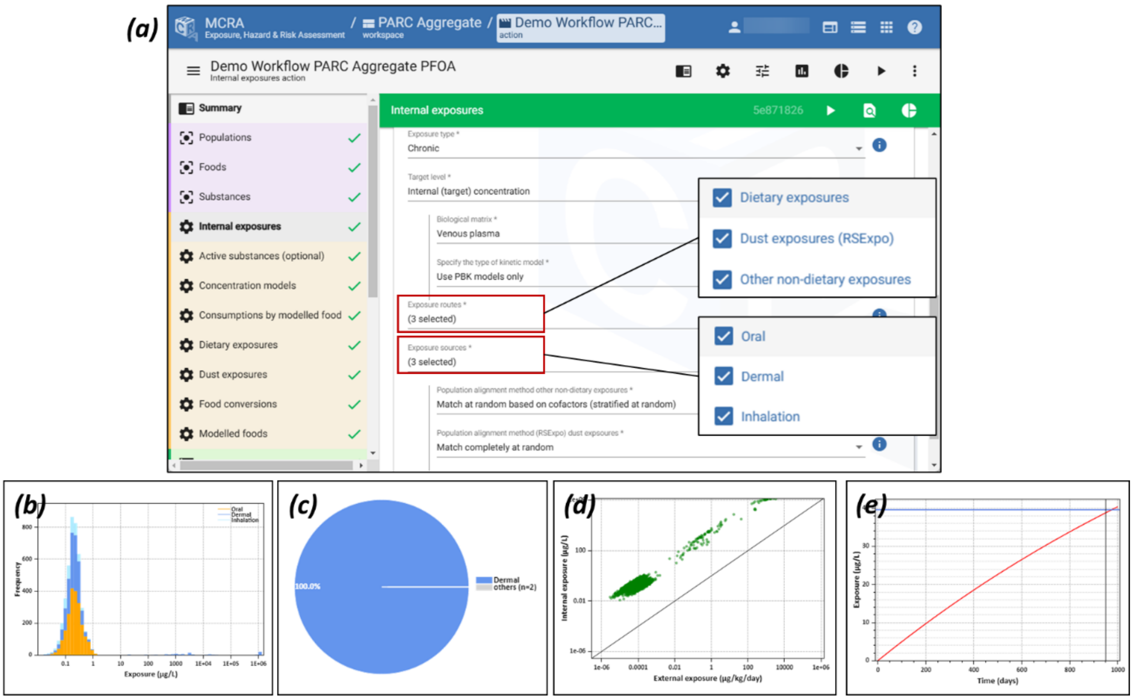
[4] AD8.4: Initial results of the application of the integrative model network in use cases

[5] D8.6: First report on the development and validation of the integrative models



Exposure type * Chronic

Target level * Internal (target) concentration

Biological matrix * Venous plasma

Specify the type of kinetic model * Use PBK models only

Exposure routes * (3 selected)

Exposure sources * (3 selected)

Population alignment method other non-dietary exposures * Match at random based on cofactors (stratified at random)

Population alignment method (RSExpo) dust expsoures * Match completely at random

☑ Dietary exposures
☑ Dust exposures (RSExpo)
☑ Other non-dietary exposures

☑ Oral
☑ Dermal
☑ Inhalation

Figure 11. presents the main user interface of the workflow for aggregate exposure assessment (panel a) along with visualizations (panels b – e) from an artificial assessment of PFOA blood concentrations resulting from chronic exposure via diet, consumer products, and dust. Panel b displays a histogram of estimated blood concentrations, highlighting also the contributions of the different routes. Panel c presents a pie chart of the contribution of each route to the total exposure distribution, with dermal being the dominating route due to the large dermal exposures shown in panel b). Panel d features a scatter plot of the internal "steady-state" exposure estimates against the combined external exposures for each individual. Finally, panel e shows the PBK model output for a single individual over the first 1000 simulated days.

3 Application of aggregate exposure in case studies

The main purpose of the case studies is to demonstrate and apply the methodological developments described in section 2 in concrete examples. The case studies are selected based on policy relevant questions, corresponding to PARC regulatory needs, in combination with scientific and policy needs proposed by partners. It should be noted that the development of the PARC model network was performed in parallel with the execution of the cases studies. Therefore, since the PARC model network was not fully ready, parts of modelling tools, existing modelling tools (not yet implemented in PARC model network) or preliminary versions were used during the case studies. Additionally, the application of the tools in the case studies provided input to the development and requirements for the PARC model network. Hence, the cases studies and PARC model network development followed an iterative, integrative process.

3.1 Source-to-dose case studies

As described in the methodological section (see 2.1.1) we could not identify a one-fits-all outdoor or indoor source to dose model. The most appropriate model or approach is to be selected in view of the purpose and scope of the case studies.

Thus, case studies are central, and driving the to be considered aspects of the full (environmental) source to dose chain. Different partners proposed case studies addressing a regulatory, scientific and/or societal question related to the impact of a source on the exposure.

3.1.1 Outdoor environment case studies

Given the interest of the partners, majority of the outdoor case studies (see 3.1.1) cover either a local pollution problem ('hotspot case studies', i.e. Pb contaminated region in Slovenia, a metal polluted region in Belgium, and a PFAS polluted region in Belgium); the key question in these case studies was the identification of main source(s) of exposure and related pathways in these contaminated regions, hence enabling local policy makers to assess the impact and select relevant exposure reduction strategies. In addition to the hotspot case studies, there was one case study addressing the role PFAS deposition on the human exposure, including back-calculation of the aerial maximum deposition to soil in order to achieve human exposure not exceeding health-based exposure guidance values.

3.1.1.1 Case study metals in around polluted sites

3.1.1.1.1Source-to-dose modelling for lead (Pb) exposure for residents living in a metal- polluted site in Slovenia, Upper Meža Valley (NIJZ, GeoZS, ARSO)

The content of the case study is currently in the publication process (under review), so we are only providing the preliminary and less extensive results of the research here.

Regulatory, scientific and societal question and case study description: Due to the long history of lead-zinc mining, smelting and also lead recycling in recent times, the Upper Meža Valley (Slovenia) is heavily contaminated with Pb, Zn and Cd. Due to the high levels of lead in the environment, a special remediation program has been set up for the Upper Meža Valley, which has been implemented between 2007 and 2022 with the aim of protecting human health, especially that of children. After the 15-year remediation program for heavy metal-contaminated environments in the municipalities of Črna na Koroškem and Mežica ended in 2022. The catastrophic flooding in the Upper Meža Valley in 2023 caused extensive damage and nullified some of the measures taken so far. As a result, new Program of Measures has been extended in 2025 to five municipalities along the Meža River: Črna na Koroškem, Mežica, Prevalje, Ravne na Koroškem, and Dravograd (PISRS 2025).

As part of the aforementioned action program to improve the quality of the environment and reduce the risk to human health, yearly human biomonitoring of blood lead levels (BLL) of 3-year-old children (aged 24 to 48 months) was carried out between 2004 and 2022 and is still ongoing at the initiative of the National Institute of Public Health. During the remediation program, a downward trend in blood Pb levels has been observed in recent years. In the past, the lead exposure of children was determined using the IEUBK model based on site-specific environmental data (limited to soil and dust levels). However, the aspect of dietary lead intake was not considered and a standard IEUBK value for diet was used. The present study closes this knowledge gap with local food values and up-to date site-specific environmental data.

Modelling approach and input data: Integrated Exposure Uptake Biokinetic Model for Lead in Children (IEUBK) was applied to predict children geomean blood lead levels (BLLs). Model was developed by the United States Environmental Protection Agency (US EPA) and has been widely used in human health risk assessments, mostly at mining and smelting contaminated sites. The environmental sources included in the IEUBK model are soil, dust, drinking water, air and diet (for more information about IEUBK model see User's guide (US EPA 2021)).

Our case study, which includes Upper Meža Valley, has been divided into three sites: Črna, Mežica and Žerjav. Environmental site-specific data were established for all three sites (average values of Pb levels were used for modelling). Dietary site-specific exposure values were established for Upper Meža Valley in general (values were the same for all three sites). Local foodstuff included were: Leafy vegetables, Root vegetables, Potatoes, Tomato and peppers, Parsley – aromatic herb, Cattle milk, Hen eggs and Brook trout's (wild). Dietary exposure value was also determined for Slovenia (based on market foodstuff lead levels). Modelling was based on various dietary exposure scenarios according to consuming market foods (uncontaminated) vs. local food (contaminated). Predicted BLLs were calculated for two age groups: Group 1 (24–36 months) and Group 2 (36–48 months). Predicted BLLs were compared to the geometric mean of measured BLLs.

Results and regulatory impact: The results of the study showed that local food consumption may be an important exposure route, which calls for precautions about dietary choices. In Figure 12Figure 13 the comparison of predicted BLLs vs. measured BLLs are shown. For both groups and in all areas, except for Group 1 in Žerjav, the use of IEUBK default diet value in modeling underestimates the exposure. Furthermore, the measured BLLs are in the range between the dietary scenarios “only market food” and “market and local food”. The scenario “only market food” assumes that children from Upper Meža Valley only consume market food, while the market and local food scenario assumes that children consume above-mentioned local foods instead of market foods, the rest are foods from the market. The latter is designated as the worst-case scenario. If we assume that the site-specific environmental values identified in this study reliably reflect the general situation in the area, the results suggest that dietary exposure can still be a significant source of lead (Pb) for children—especially in regions affected by historical lead mining. In addition, our study demonstrates that the use of IEUBK default diet values (exposure) underestimated the contribution from dietary exposure, which emphasizes the need to adapt the dietary exposure model to the specific case study. Detailed discussion and results of our study are going to be presented in the upcoming open-source paper.

Since consuming locally produced food remains among key pathways of lead exposure, it is important that families—especially those with young children living in the Upper Meža Valley—continue to make informed decisions about their dietary habits. Ongoing awareness and support are essential to help reduce potential health risks in the community, especially now after flooding in 2023, when the contaminated material was deposited on the riverbanks where people have gardens and lawns.

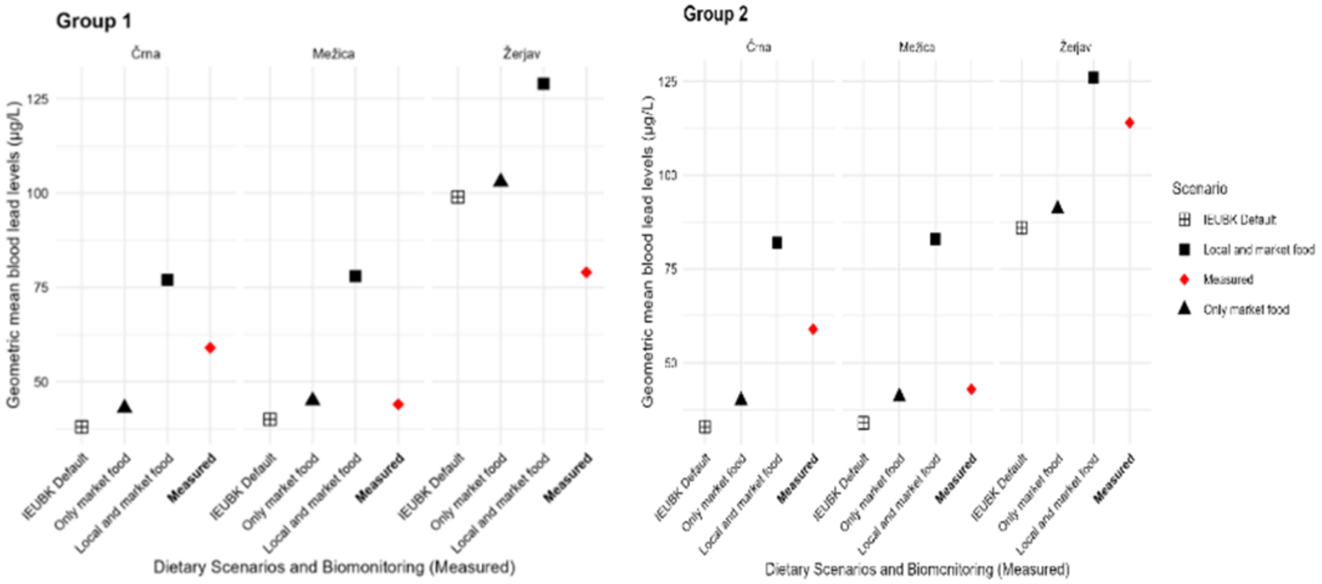


Figure 12. Comparison of the observed blood lead levels (BLLs) derived with IEUBK modelling with estimated BLLs values for Group 1 (24-36 months) and group 2 (36-48 months) in studied areas (Črna, Mežica, Žerjav). Observed values according to dietary scenarios (Only market food, Local and market food) and IEUBK default dietary value are presented.

3.1.1.1.2 Source-to-dose modelling for Arsenic and comparison with HBM data for teenagers living in a metal polluted site, Umicore site (Belgium, VITO)

The full report has been published in Dutch (PIH and al. 2024). This report includes a full description of the HBM study population, an analysis of the observed health effects in the study population, an analysis of the questionnaires on the participants’ lifestyle and attitude towards pollution, and the source-to-dose and PBK modelling.

Regulatory, scientific and societal question and case study description: In the Northern Campine region in Belgium (Hoboken, Kruibeke and Hemiksem), there is concern about environmental pollution because of the proximity of a metal smelter/recycling company in Hoboken. Over the years, measures have been taken by the authorities and the company to reduce emissions of metals into the environment. Both based on environmental measurements and through the biannual blood tests (on lead) on children, a downward trend in exposure to metals was observed in recent years. Nevertheless, there were also worrying signs, such as several fires at the site and an increased lead level in children’s blood during the COVID-19 lockdown. Local residents have long been calling for a thorough assessment of the risk to health among the public, not only in terms of lead blood levels in young children (which is the focus of the existing internal exposure monitoring program), but also for other environmental pollutants (e.g. cadmium and arsenic) to which residents around the plant are exposed. Until 2023, environmental monitoring of Cd and As was focused on monitoring Cd and As in air; in 2023, complementary monitoring in dust, soil, and local foods was performed, together with a HBM study (As, Cd, Pb) in 200 teenagers (13.5-17y) living in this region. The modelling work performed within PARC aims to provide an answer on the relative contribution of the exposure routes and sources, in order to assess relevant exposure reduction measures.

Modeling approach: The purpose of the exposure calculations was (i) to determine the extent to which the various exposure pathways contribute to the total external oral and inhalation exposure, and (ii) to verify the modelling predictions with HBM data. The modelling work was focused on As as for this substance the largest knowledge gaps regarding exposure routes exist.

Since arsenic occurs under different chemical forms (speciation), it was decided to perform external exposure modeling for the more toxic inorganic arsenic compounds. The external exposure calculations were performed with S-Risk (i.e. one of source to dose models described in **Erreur ! Source du renvoi introuvable.**. See Annex 5.5). This model considers all relevant exposure routes and has been parameterized for the Flemish context in the past. This adaption to the local context includes amongst others Belgium-specific food consumption patterns and soil properties. The food consumption patterns consist of the average consumption of different foodstuffs in different age categories, based on the Belgian Food Consumption Survey of 2006 (De Vriese et al. 2005; Seuntjens, Steurbaut, and Vangronsveld 2006). As part of the exposure calculations, 5 distinct residential areas were delineated based on their distance and wind direction from the metal smelter/recycling company. Calculations were performed for the most contaminated zone (zone 1) and for a zone representative of all other zones of the study area, i.e. zone 2. The As levels in environmental matrices differed significantly between zone 1 and the zones 2-5, and did not differ significantly between zones 2-5. For both residential zones (zones 1 and 2), 4 exposure scenarios (as defined in the model S-Risk) were calculated i.e. 1), Ornamental garden (no vegetable garden and no chicken coop), 2) Vegetable garden (vegetable garden and no chicken coop), 3) Chicken coop (no vegetable garden and chicken coop) and 4) Vegetable garden and chicken coop.

The external exposure calculations for each scenario were conducted based on the environmental As levels per zone, and not on the level of the individual participants. Median environmental As levels were used in baseline calculations, while in additional calculations both the upper and lower bound of the background exposure through commercial food was used (EFSA 2021), and the P25 and P75 of soil and air concentrations.

S-Risk does not contain formulas to convert external exposure to **internal (urine) concentrations**. Therefore, it was opted to use an R-based PBK model (physiologically based pharmacokinetic) for arsenic. This model is based on the model of El-Masri and Kenyon (2008), combined with equations that model the evolution of the body throughout the life span (Gastellu et al. 2025). These equations are used to model a virtual population to obtain a distribution of urine concentrations instead of a single value. The distribution of urine concentrations is based on the variation in the virtual population, not on the variation of external exposure values. This improved model was created under PARC T6.2.2 by Thomas Gastellu, at the time a PhD student at Oniris and ANSES.

The PBK model input distinguishes between As(III) and As(V) for the inorganic As compounds. Since speciation of arsenic was not measured in the environmental samples, a distribution factor As(III)/As(V) was applied... Hereto, based on a literature review, the shares of As(III) and As(V) were estimated for the different external doses.

The PBK model takes into account metabolization of As(III) and As(V). As a result the concentrations of As(III), As(V), DMA, MMA and TRA (toxic relevant arsenic; sum of the preceding speciations) in urine could be predicted over the lifetime. The predicted urinary concentrations for teenagers were then compared with measurements from this study. Dermal exposure was not included in the PBK model since the external exposure calculations indicate that this pathway is negligible.

Model parameterization: see Technical guidance document S-Risk (Cornelis et al. 2022). The technical guidance document describes amongst others the ingestion rates (soil, food, water), inhalation rates, body weights and time patterns per scenario for all different age groups (, and described arsenic specific model parameters such as biotransfer factor (from soil to eggs) and bioconcentration factors (from soil to vegetables).

Input data: Environmental concentrations.

Table 1. Environmental arsenic concentrations in case study Arsenic exposure in N campine region (Flanders)

Matrix	Zone 1	Zone 2	As(III) (%) – As(V) (%)
Soil (mg/kg dw) (P25 – P50 – P75)	25.7 – 36.5 – 82.6	10.0 – 15.0 – 28.0	5 - 95
Air (ng/m^3) (P25 – P50 – P75)	3.37 – 3.94 – 4.75	1.58 – 1.78 – 1.97	30 - 70
Local vegetables	Based on BCF from soil		40 - 60
Local eggs	Based on BTF from soil		0 - 100
Tap water (µg/L)	0.52	0.52	0 - 100

Background values in commercial food and food consumption patterns (EFSA et al. 2024). For this a 50-50 ratio As(III)/As(V) was used instead of the 40-60 for vegetables alone, as it contains more foodstuffs than vegetables which have a different As(III)/As(V) ratio.

Results and discussion: The **external exposure** doses for zone 1 and zone 2 for the age group 10-15 years were calculated (Table 1). For both zones, the lower bound (LB) and upper bound (UB) for background exposure via food were used in the calculations. The difference between the two zones is mainly due to the local contribution via home-grown eggs and home-grown vegetables due to a difference in soil concentration. **Local eggs always emerge as the main local exposure source**, but concentrations in eggs are potentially overestimated by the S-Risk model (0.017-0.05 mg/kg fw measured (*n* = 4 in zone 2) *vs*. 0.09-0.27 mg/kg fw modeled for P25 and P75 soil concentration in zone 2). The percentage of young people consuming eggs and/or vegetables from their own garden/chicken coop in zone 1 is low (1 in 50 participants, based on questionnaire); therefore, for this group the comparison of the exposure dose should be made for the 'ornamental garden scenario'; then the difference in oral exposure between the two zones is limited. Indeed, in this case there is only a contribution via ingestion of drinking water, ingestion via soil particles, ingestion of dust particles and background exposure via food, with background exposure via food contributing the most to total oral exposure (see Figure 13). **If local eggs or vegetables are consumed, exposure increases. This shows that the advice regarding the consumption of local food is justified.**

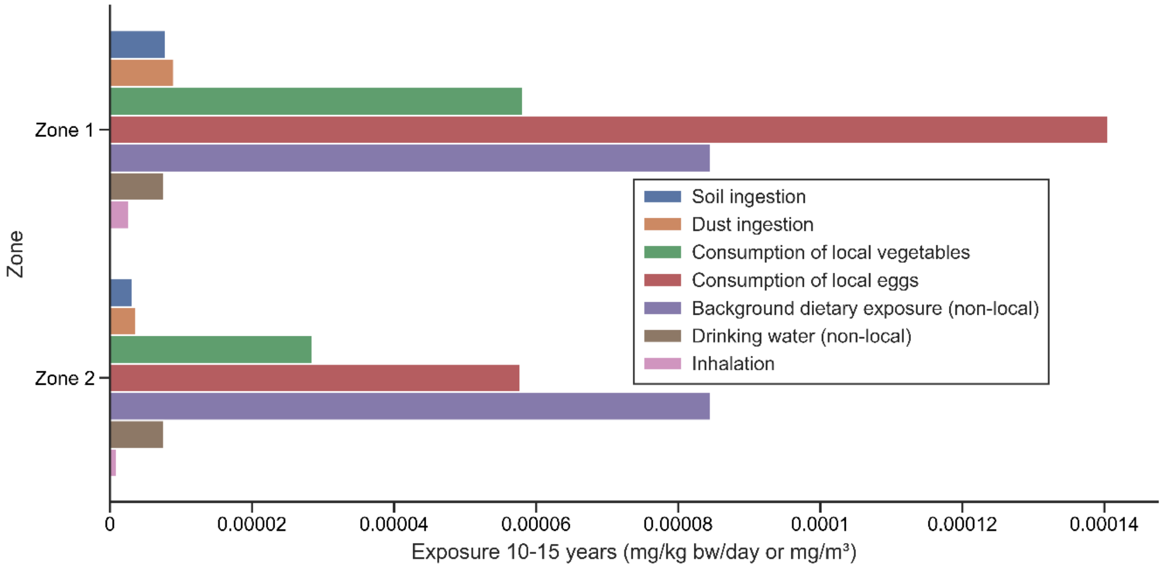


Figure 13. Comparison of the contribution of different exposure routes for the two zones. For both zones the upper bound (UB) of the background exposure through commercial food is given. The exposure routes of local egg and vegetable consumption are included to highlight their importance.

As a final step, the modeled urine concentrations of TRA were compared with the measured urine concentrations. Both modeled and measured urinary concentrations were normalized based on creatinine. For all scenarios calculated for external doses, urine concentrations were also calculated using the PBK model. In this part, however, we limited the comparison with the modeled concentrations for the ornamental garden scenario. Indeed, the questionnaires revealed that most participants did not eat homegrown vegetables or eggs, making the ornamental garden scenario the most appropriate scenario to compare with.

For Zone 1, TRA concentrations were underestimated when the LB background dietary exposure is used but were largely adequately predicted when the UB background exposure is used where 62% of the measured values fall within the 5-95th percentile of the modeled values.

For Zone 2, the trend was identical to Zone 1 in that the measured TRA concentrations in urine were adequately predicted when the UB background exposure was used where 58% of the measured values fall within the 5-95th percentile of the modeled values.

In the scenario where no local food is consumed the uncertainty related to treatment of non-detects in commercial food (UB vs LB approach) appears to have the highest contribution to the overall uncertainty. In this scenario the uncertainty and variability in the soil concentration plays only a minor role since direct soil and dust ingestion have only a small contribution to the aggregate exposure. However, if we consider the consumption of local food, the soil concentration variability becomes the main driver of the external exposure uncertainty and variability through its effect on the concentration in eggs and vegetables. The variability in the PBK model outcomes reflects the variability of the virtual population which was modeled with point values for the external exposure as input. Incorporating the variability of the environmental measures in the external exposure estimates would give more realistic results and increase the variability in the PBK model outcomes.

Regulatory impact and further reflections: This case study gave insight into the relative importance of different exposure routes for arsenic. Local vegetables and eggs are an important exposure route, however only a low number of participants consume local food. This indicates that the previous advice on limiting local food consumption in this contaminated area, based on lead pollution, is valuable to decrease arsenic exposure as well. Finding from this scenario-based modelling can support finding from statistical associations between arsenic and intake via vegetables and eggs, and have an additional value since scenario-based modelling does provide also in a quantitative way (e.g. % of aggregate exposure) the relative contribution by routes and source, and scenario based modelling overcomes sample size issues which may occur in finding statistical associations between levels in serum and sources of exposure.

3.1.1.1.3 Identification of lead sources from blood samples for residents living in a hotspot region in Belgium, using lead isotopes (ISSeP)

Regulatory, scientific and societal question and case study description: Soils in the urban area of Liège show high Pb concentrations, potentially contributing to higher blood Pb levels in for residents in this area. This case study investigated the potential of lead radiogenic isotopes to evaluate the contribution of soil Lead to lead in blood, while investigating also other potential sources of exposure and the role of behavioural, socio-economic and dietary habits.

Approach and input data and results: The study uses the measurement of Pb radiogenic isotope composition, a well-known tool assisting geochemists in the identification of environmental Pb source and in the evaluation of their relative contributions and mixing relationships within samples. The principle of using these geochemical proxies is built on the idea that current blood lead levels (BLL) in communities exposed to contaminated soils experience a range of Blood Lead Isotope (BLI) compositions reflecting a mixing trend between the soil isotopic composition (presumably being the main exposure source) and the isotopic compositions of other sources, including the "Natural background", with very distinct isotopic compositions (more radiogenic), and "Anthropogenic Pb", mostly less radiogenic.

This study also intends to complement the current knowledge on BLI signature and its evolution, since it provides the most comprehensive dataset for high-precision radiogenic isotopes of lead in blood for the western European population In particular, it investigates the potential of high precision Pb isotope measurements in understanding the contribution of Pb from contaminated soil to Pb in blood in a community setting, while investigating also other potential sources of exposure potentially significant in explaining blood lead isotope signatures.

Human biomonitoring and environmental surveys involved 81 adults and 4 children living in the urban area of Liège (Belgium), with a large collection of soil and vegetable samples (Petit et al. 2022). Soils in the area show moderate (median of 360 mg/kg) to high (95th percentile of 1000 mg/kg) Pb concentrations, due to former metal processing activities. Blood Lead levels (BLL) were associated with age, smoking status, Pb pipes at home, age of dwellings and gardening/homegrown eating habits. They were also quantitatively consistent with a ~ 20 % increase due to the exposure to Pb from soils compared to the general adult population, as estimated by a single-compartment biokinetic model. Consistently, as seen on Figure 14, their isotopic composition does not represent an endmember that fully accounts for the variability of Blood lead isotope (BLI) compositions measured in the study population (as soils show intermediate isotopic compositions, within the range of those measured in blood). In fact, BLI signatures showed statistically significant associations with allotment attendance frequency but also with the age of dwellings, the presence of Pb pipes at home, country of birth and the use of traditional food containers, i.e. not exclusively soil-related.

Extrapolation of BLI data from the study group with a one-compartment biokinetic-isotopic model suggests that the general adult population still records the Australian Pb ore signature in blood, which was of economic interest in the manufacture of tetraethyl Pb in Europe up until 2000's.

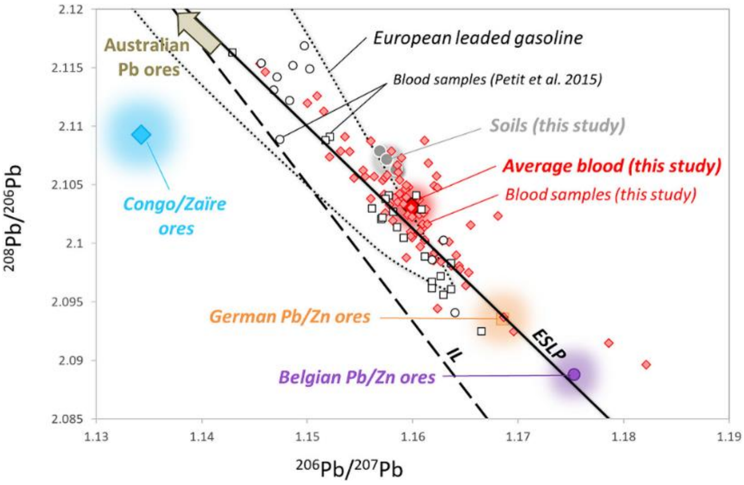


Figure 14. Tri-isotope plot for soil and blood lead data from this study (red diamonds - large symbol size corresponds to the population average) and from (Petit et al. 2024) (1976–1978: white dots; 2008–2009: white squares). « EU Leaded Gasoline » fields from (Komárek et al. 2008). "Industrial Line" IL and « European Standard Lead Pollution » line ESLP from (Véron et al. 1999) and (Haack et al. 2003), respectively. Data on Belgian ores (purple circles), German (orange squares) and Congo/Zaïre (blue diamonds) ores, and Australian ores (out of range) are compiled from (Dejonghe 1998); (Doe and Rohrbough 1977) and (Sangster, Outridge, and Davis 2000), respectively.

Comparison of recent (2018, this study) BLI ratios with those measured in 2008 (Petit et al. 2015) indicate they have remained unchanged during the last decade, despite decreasing exposure in the general population. This would further suggest that the balance between different environmental Pb sources/routes of exposure (if they would have hypothetically contrasted isotopic signatures) has not changed significantly over this recent period, Scattered BLI signatures along the ESLP line (Figure 14) suggest that the stock of metallic Pb in use as well as diffuse environmental contaminations relevant to human exposure likely integrates various isotopically distinct sources of Pb refined from ores of different origins including Australia. This may certainly account for the very variable BLI values observed in the study population.

While some individuals show more thorogenic BLI ratios (relatively more enriched in 208Pb), which could be consistent with a greater exposure to local soils and/or by their country of birth, the BLI data mostly follow a trend roughly parallel to the European Standard Lead Pollution (ESLP) line (model defining the array formed by the isotopic composition of environmental samples in NW Europe), within the European leaded gasoline field, even two decades after the withdrawal of this source (Figure 14). Differences in BLI are probably associated with factors related to the presence of Pb in dwellings (pipes, paint) and drinking water distribution system, suggesting that the anthropogenic Pb in use, relevant to human exposure, may contain ore components of different origins, including the Australian Pb ore signature. The full study is available for download (Petit et al. 2024).

Regulatory impact and further reflections: As for elemental concentrations, the potential of Pb isotopes is limited by an extensive sampling of environmental matrices and the knowledge of individual exposure history (since Pb builds up in the body with time). In addition, the current knowledge of blood Pb isotope signatures in the European population is yet very limited to make it a robust and stand-alone parameter to monitor. If Pb isotopes are proven environmental geochemical tracers, examples of regulatory sciences/decisions based on Pb isotopes signatures are few in the context of environmental health and are still to be complemented and constrained by other relevant environmental data. With these constraints, the potential of Pb isotopes, in linking biological data and environmental contaminations, may provide valuable insights to quantitative and qualitative exposure assessment.

3.1.1.2 Source to dose modelling for PFAS

3.1.1.2.1Determining threshold values for PFAS in aerial deposition (VITO)

The full report has been published in Dutch (Van Holderbeke and al. 2024).

Regulatory, scientific and societal question and case study description: Currently, there is no assessment framework for PFAS in aerial deposition, so the risks of exposure to PFAS through deposition cannot be assessed. The Flemish Environment Agency (VMM) is the responsible body in Flanders for air policy and a partner to improve air quality and tackle air pollution. For this purpose, the VMM monitors, among other things, levels of PFAS in ambient air and in deposition, i.e. aerial fluxes to the terrestrial environment. The objective of this case study is to determine health-based thresholds values for PFAS in air and deposition, considering exposure sources and routes arising from aerial deposition. The derived values can be used in the evaluation of measured concentrations, in the drafting of environmental permit conditions, in environmental impact assessment (EIA) guideline books and/or the regional (Flemish) environmental regulations. This case study focusses on PFOS and PFBA, which were selected based on their relatively high occurrence in air and deposition in Flanders compared to other PFAS compounds, their toxicity and the availability of toxicity, environmental occurrence and transport data. Additionally, by addressing PFOS and PFBA we address compounds across different PFAS groups (PFOS: long chain and sulfonic acid; PFBA: short chain and carboxylic acid).

Modeling approach: Aerial deposition affects different pathways and sources in the source to dose environmental chain (see 2.1.1); therefore, the modelling approach needs to account for this complexity.

Hereto, two modeling approaches were followed, each with their own specific protection target:

1. Approach 1: The maximum permissible deposition flux (µg/(m^2 day)) was calculated. This calculation is based on current PFAS levels in soil and groundwater. The objective is to stay below the Flemish target values for soil (PFOS and PFBA) and groundwater when this deposition flux takes place over a 100-year period. These calculations were done using the F-Leach model (Joris, Van Looy, and Bronders 2015). Target values for PFBA: 2.5 µg/kg dm (soil), 6000 ng/L and 100 ng/L (groundwater). Target values for PFOS: 3 µg/kg dm (soil); 4, 100 and 120 ng/L (groundwater).
2. Approach 2 (health/risk based): The deposition fluxes determined in approach 1 were used as input to calculate the aggregate human external exposure in various exposure scenarios (agriculture, residential and industrial). Exposure routes include (i) soil and dust ingestion, drinking water, inhalation and consumption of commercial food (background) (for all scenarios), (ii) locally grown vegetables (residential scenario) and (iii) and egg and cattle consumption (agricultural scenario). The aggregate human external exposure was calculated using S-Risk (https://s-risk.be/en). The model takes into account exposure at different life stages, and scenario specific exposure factors. Human exposure was then compared to available health-based guidance values (PFBA: chronic oral RfD (US EPA 2022), PFOS: TWI for EFSA-4 (EFSA 2020)). For PFBA the calculations indicated children 1-6 years as the most sensitive group

(agriculture and residential), and adults in the industrial scenario. For PFOS, adults were taken as the most sensitive group based on the EFSA TWI which is based on pregnant women.

Model parameterization: see Technical guidance document S-Risk (Cornelis et al. 2022). The technical guidance document describes amongst others the ingestion rates (soil, food, water), inhalation rates, body weights and time patterns per scenario for all different age groups, and described PFOS and PFBA specific model parameters such as biotransfer factors (from soil to eggs) and bioconcentration factors (from soil to vegetables) (updated values for PFOS and PFBA: see section 3.2.1.8 (p. 42) and section 4.2.1.4 (p. 81) in (Van Holderbeke and al. 2024).

Input data

Table 2. Environmental monitoring data, current situation, see (Van Holderbeke and al. 2024) for more details

Matrix	**PFOS**	**PFBA**
Soil (µg/kg dm) – current background levels in Flanders	1.5	1.25
Air (ng/m^3)	0.0283	0.0365
Background deposition (ng/(m^2 day))	5.8	3.12
Local vegetables	Based on BCF from soil	
Local eggs	Based on BTF from soil	
Dietary exposure via commercial food (background exposure) (mg/(kg bw day))[6]	5.14×10^{-8}	6.27×10^{-7}

Results and discussion:

PFBA: A deposition threshold value of 0.14 µg/m^2.day was calculated, based on the assessment value of 100 ng/L for the sum of 20 PFAS in groundwater (Van Holderbeke and al. 2022). This means that at a deposition flux of 0.14 µg/m^2.day the 100 ng/L is reached in groundwater after 100 years. Additional comparable calculations using this approach were made for different soil and groundwater target levels, giving rise to less strict deposition threshold values.

This deposition threshold value was used as input for the aggregate human external exposure calculations (approach 2), where the total oral exposure did not exceed the chronic oral RfD for PFBA (US EPA 2022).

Several remarks were given to the policy makers to adopt a safety margin:

- 100 ng PFBA/L is reached in groundwater after 100 years.
- When using the background concentration in soil of 1.25 µg/kg dm as a starting concentration (instead of 0 µg/kg dm as starting point), the 100 ng/L is reached before 100 years through leaching without additional deposition.
- On several locations in Flanders a concentration in groundwater of 20 ng/L PFBA has been measured.

PFOS : A deposition threshold value of 3.3 ng/m^2.day was based on the limit value of 4 ng/L for the sum of the 4 EFSA PFAS in bottled water and water used for the production of foodstuffs (Superior Health Council 2024). Additional comparable calculations using this approach were made for different soil and groundwater target levels, giving rise to less strict deposition threshold values. This deposition threshold value was used as input for the aggregate human external exposure calculations (approach 2), where the total oral exposure did not exceed the TWI for EFSA-4, (EFSA 2020) under the assumption that PFOS dominates (since exposure to PFNA, PFHxS and PFOA are not taken into account in the calculations).

Several remarks were given to the policy makers:

- The 3.3 ng/m^2.day deposition is lower than the 2024 background average deposition levels in different land use scenarios: agricultural background is 3.9 ng/m^2.day, residential background is 7.4 ng/m^2.day and industrial background is 8.6-19 ng/m^2.day in Flanders. These values will be adjusted as new data becomes available. It is advised to issue deposition threshold values lower or equal to the background deposition values to avoid further PFOS accumulation. As the 3.3 ng/m^2 day is below the average background deposition levels in the different land use scenarios, the 11.37 ng/m^2 day for agriculture and 82.6 ng/m^2 day for residential and industry could be used as temporary threshold values. These deposition thresholds do not give rise to an exceedance of the TWI for EFSA-4 in their respective land use scenarios.

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[6] Lower bound average values, example for the age group 21-<31y. For each age group the corresponding exposure doses were used in the calculations

- When using the background concentration in soil of 1.5 µg/kg dm as a starting concentration, the 4 ng/L is reached before 100 years through leaching without additional deposition.

The relative contribution of the different exposure routes for the different land use scenarios is depicted in Figure 15. The figure highlights, that, while the origin/source (aerial deposition) is related to the aerial compartment (and this is also visible in the significant exposure via air, to aggregate exposure), it also affects and has a large contribution to subsequent other routes and sources of exposure, i.e. mainly via vegetables affected by deposition for PFBA, and local animal product (cattle) for PFOS. This implies that an integrated exposure assessment, throughout the full source to dose chain is warranted.

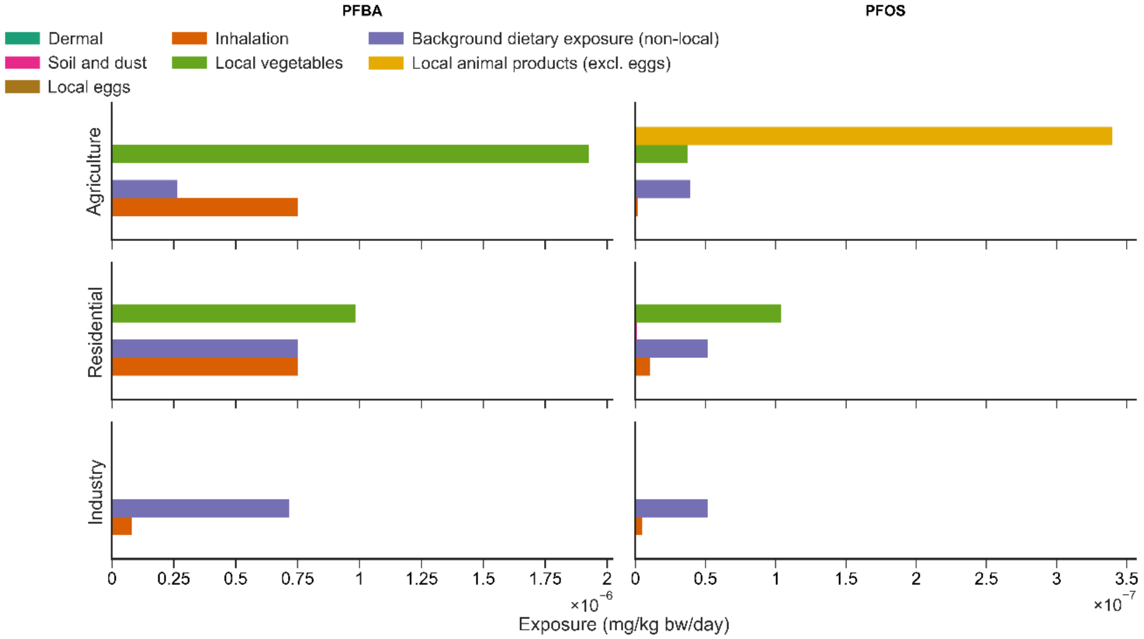


Figure 15. Relative contribution of the different exposure routes for different land use scenarios. These contributions were calculated at a deposition of 0.14 µg PFBA/m^2 day and 11.37 ng PFOS/m^2 day (agriculture) and 83 ng PFOS/m^2 day (residential and industry).

Regulatory relevance: This case study has direct regulatory relevance as it provides a scientific basis for deposition thresholds for PFOS and PFBA, as was requested by the Flemish Environmental Agency.

3.1.1.2.2PFAS exposure among teenagers living in a hotspot near a PFAS production site in Flanders (VITO)

The full report is published in Dutch: (Consortium UAntwerpen et al. 2023).

Regulatory, scientific and societal question and case study description: From 2019, a PFAS action plan was established for Flanders, due to results of ongoing biomonitoring studies and increasing knowledge on the adverse effects on human health (EFSA 2020; Vrancken 2021). The efforts with regards to this action plan accelerated when ground works revealed PFAS contamination in the soil around the 3M plant in Zwijndrecht, Belgium (Figure 16). This was strongly mediatized, with simultaneous increasing political attention. In April 2021, the Flemish Care Department issued an advice to residents to avoid consumption of local eggs, and to limit consumption of home grown vegetables and groundwater (De Brouwere and al. 2021) based on available measurement data, scientific literature, and a recent PFAS contamination case in Dordrecht, the Netherlands (Boon and al. 2021b, 2021a; Gebbink and van Leeuwen 2020; Geraets 2021). These would be temporary measures that the public could immediately adopt to limit exposure, pending more detailed measures based on an environmental and human biomonitoring campaign. One of these campaigns, initiated by the Flemish Department of Environment, focused on adolescents. The goal was to investigate to what extent the adolescents were exposed to PFAS, map the routes of exposure and how this was related to their health. Blood, urine and environmental samples from their living environment were collected to shed light on these questions. The monitoring programme was set up outside PARC. This connection with PARC lies in the assessment of exposure routes and sources, which is investigated in this PARC case study.

Modelling approach: The approach to modeling human exposure is twofold. First the external exposure was modeled, after which this modeled external exposure was used to model the internal exposure. The focus is on the oral exposure route, as this route in general is the dominant exposure route for PFAS (ATSDR 2021; Poothong et al. 2020a). For the exposure modeling we focused on the six compounds that were >LOQ in ≥60% of the serum samples: $PFOS_t$, $PFOA_t$, PFNA, $PFHxS_t$, PFBA and PFDA where the subscript 't' stands for total = linear + branched forms of the PFAS compounds

External exposure was modeled using S-Risk (Cornelis et al. 2022) and internal exposure using MERLIN-Expo (AFRY 2015). The S-Risk model considers all relevant exposure routes and has been parameterized for the Flemish context. This adaption to the local context includes amongst others Belgium-specific food consumption patterns and soil properties. MERLIN-Expo contains a generic PBK model that has been parametrized for PFOS and PFOA (Brochot and Quindroit 2018). At the time of this case study the improved PFAS PBK models from PARC T6.2.2 were not yet available.

This was done for different land use scenarios and 5 spatial zones, roughly corresponding to municipalities. All 5 spatial zones were within 5 km distance of the PFAS production site.

Input data: One or more environmental samples were collected from 82 gardens of participants. The different types of environmental samples (*n*) were soil (vegetable garden (62), chicken coop (38) and/or greenhouse (10)), compost (36), rainwater (54), vegetables (59), fruit (62), nuts (7) and eggs (37). Additionally, 129 house dust samples were collected. More information on the samples and sample collection is given in the report (Consortium UAntwerpen et al. 2023). Background exposure through the consumption of commercial food was based on the average lower bound data for Belgium reported by EFSA (EFSA et al. 2020).

Model output, results and discussion

External exposure: Results for the external oral exposure, with a distinction between the different spatial clusters and scenarios, are shown in Figure 16. In some spatial clusters the number of vegetable or egg samples were too low to calculate scenarios using these exposure routes.

The most important exposure route for the sum of EFSA 4 is consumption of home-grown eggs (because of the contribution of $PFOS_t$), followed by home-grown vegetables. Exposure via soil and dust inhalation or tap water (due to permeation through water pipes) is negligible in the total oral exposure for the sum of EFSA 4. Background exposure through commercial food is not negligible but is much lower than exposure through home-grown vegetables or eggs. Whereas no population representative data on prevalence and frequency of home-grown eggs exist for Flanders, data from questionnaires in a HBM study (300 participants) indicate that is it a quite common practice in some region (nearly 10% of participants report to consume home grown eggs), and probably also in other regions in Flanders.

For the sum of the EFSA 4 ($PFOS_t$, $PFOA_t$, PFNA and $PFHxS_t$), it is noteworthy that the EFSA TDI (EFSA 2020) (0.63 ng/(kg bw × day), purple line on Figure 16, is exceeded as soon as home-grown vegetables or eggs are consumed. This is not unexpected as for adolescents the daily intake through commercial food (background exposure) is already close to the TDI, so that in principle any additional exposure should be avoided. It should be mentioned that EFSA 2020 TDI is mainly applicable for adults, however, it was used here as a reference for adolescents. $PFOS_t$ dominates the EFSA 4 exposure in the scenario 'residential exposure with chicken coop'. When consumption of home-grown vegetables from the vegetable garden is considered, $PFHxS_t$ exposure becomes an important contributor as well. The lowest contribution to oral exposure for the sum of EFSA 4 comes from PFNA in this region.

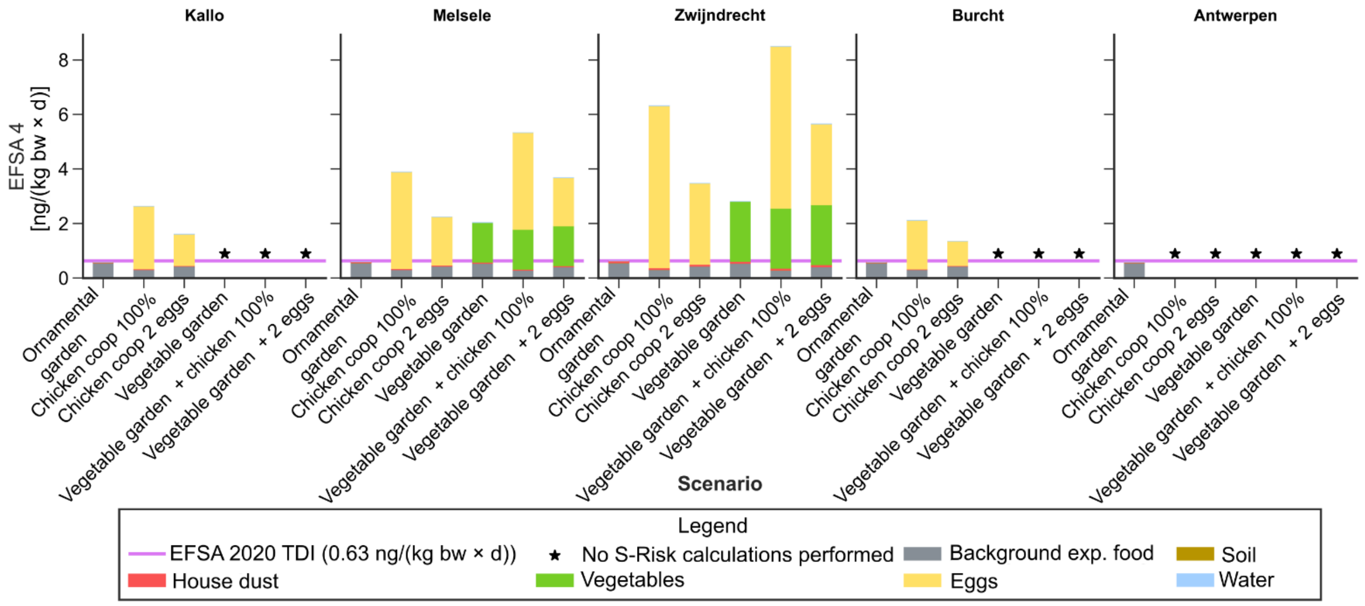


Figure 16. External oral exposure doses for the sum of the EFSA 4 compounds for 5 distinct zones (municipalities) within the study area. The contribution of the considered exposure routes is indicated by different colors. For some regions not all scenarios are calculated (indicated by '*') as no environmental measurements were available for that region.

When PFAS oral exposure is compared across the different scenarios, the total oral exposure dose is always lowest for the ornamental garden scenario, where the oral exposure is mainly determined by the background exposure via commercial food (Figure 16, ‘Ornamental garden’ scenario), and to limited extend by soil and dust ingestion. The total oral exposure is highest for the scenario with ‘Vegetable garden and chicken coop’ scenario with 100% consumption of home-grown eggs (~4 eggs/week). Exposure via egg consumption is halved when switching from 100% consumption of home-grown eggs to 2 home-grown eggs per week.

Depending on the PFAS compound considered, exposure via home-grown vegetables or eggs is more important (separate figures for each of the 6 PFAS considered PFAS compound are available in the full report, and briefly described in this paragraph). The impact of consumption of home-grown vegetables is negligible for $PFOS_t$. For $PFHxS_t$, the contribution of home-grown vegetables is higher than for other PFAS. The contribution of home-grown vegetables to total oral exposure is $PFHxS_t$ > PFDA > PFBA >$PFOA_t$ > PFNA and negligible for $PFOS_t$. This can partly be explained by the bioconcentration factor (BCF) of these compounds. Ghisi, Vamerali and Manzetti (Ghisi, Vamerali, and Manzetti 2019) found that the BCF of PFBA is typically much larger than PFOA and PFOS for several crops. Wang et al. (Wang et al. 2020) found that the BCF of PFBA is the highest, then PFHxS, while the BCF of PFOA is slightly higher than PFNA, and the BCF of PFOS is similar to the BCF of PFOA. The data in this study indicate a higher BCF for PFOA than for PFOS. The bioconcentration of the different compounds depends on the crop type, plant compartments, soil properties etc. (Felizeter et al. 2021; Lesmeister et al. 2021; Zhang et al. 2020).The oral exposure of the different PFAS compounds through vegetables also depends not only on the BCF, but also on the soil concentrations and the contributions of the different vegetables to the total diet. The consumption of home-grown eggs weighs most heavily on exposure to $PFOS_{t,}$ but also for the other PFAS there is a significant impact of egg consumption on total exposure for most residential areas. Previous research in the vicinity of the 3M plant also found that PFOS was the dominant compound in home-grown eggs in this region (Lasters et al. 2022).

Internal exposure: Correlation calculations between PFAS in the environmental samples and PFAS in serum as well as determinant analyses confirm the important contribution of local food consumption to serum PFAS levels. To further verify the external exposure assessment, serum PFAS levels were estimated using a PBK model incorporated in MERLIN-Expo.

For PFOSt, the predicted serum concentrations for the different scenarios and the Zwijndrecht region are shown in (Figure 17). The PFOSt, the predicted serum concentrations are lower than the average measured values in serum for all modeled residential zones except the scenarios ‘Chicken coop 100%’ and ‘Vegetable garden + eggs 100%’ for Zwijndrecht. The impact of consumption of homegrown vegetables (cfr. vegetable garden scenario) on predicted serum concentrations is limited, in the same order of magnitude as the scenario ‘ornamental garden’. The exposure is calculated over the course of a lifetime, with a higher exposure for young children, followed by a decrease during adolescence after which the exposure slightly increases during adulthood. Serum measurements are only available for adolescents so the exposure can only be compared in this age range.

The predicted serum concentrations are highest in Zwijndrecht > Melsele > Kallo, Burcht and Antwerp, following the same ranking of the average PFOS$_t$ serum measurements in those zones. It appears as if the PFOS$_t$ serum concentrations are underestimated for all residential zones (for figures, see report). Some possible causes/explanations could be: (i) the current approach assumes the external environmental exposure was constant over time at the current levels. This could be an underestimation, as it is reasonable to assume environmental levels were higher in the past, closer to the period when there was active production at the fluorochemical plant. Mothers living in the area during prolonged times and consuming local produce before the no-regret measures were in force could have increased their children’s blood level through placental transfer and breastfeeding; both contribuions could possible still be relflected in the HBM monitoring data while ignored in the current modelling approach.

(ii) a number of exposure sources and/or pathways are not included in the modeling. Indeed, the exposure modeling in this study does not consider exposure via consumer products such as cosmetics and PFAS-containing cookware or the use of PFAS-containing sprays; however, this additional contribution is likely to relatively small and comparable to the general population (see 0), since it is not related to elevated environmental contamination.

(iii) Possibly underestimating exposure via tap water (drinking water). When using preliminary drinking water measurements from the Vlaamse Milieumaatschappij (Milieumaatschappij 2022) which are in the range of 0.5-10 ng/L in the study area instead of the EFSA lower bound concentration of 0.61 ng/L (EFSA Appendix A - Table A.4), the estimated serum concentrations could be up to 0.5 µg/L higher.

(iv) For a number of residential areas, only scenarios with limited exposure were calculated due to a lack of environmental measurements (e.g. for Antwerp only ‘Ornamental garden’, for Kallo and Burcht only ‘Ornamental garden’ and ‘Chicken coop’). However, the measured serum concentrations may originate in part from participants who do eat home-grown vegetables or eggs (for Antwerp).

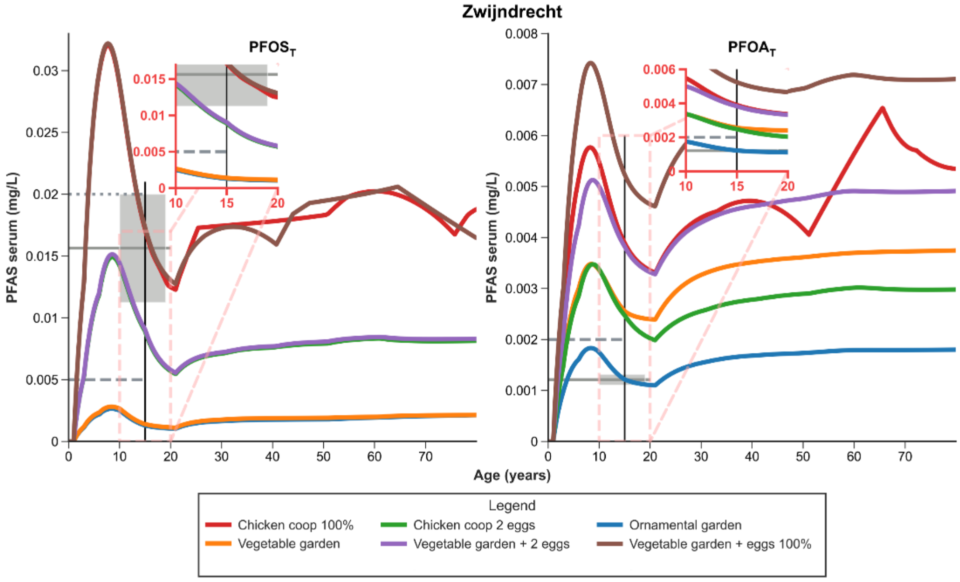


Figure 17. Output of the internal exposure calculations for PFOSt and PFOAt for the Zwijndrecht region. Each panel displays the time traces of the calculated serum concentrations. The differently colored lines indicate the calculated serum concentrations for each of the scenarios. The black vertical line is at age 15 years, which is also where the insets focus on. The dashed and dotted lines indicate the HBM I and HBM II levels, respectively. The horizontal dark gray line indicates the average PFOSt or PFOAt serum concentration for Zwijndrecht, with the 95% confidence interval around this average indicated by the lighter gray band.

For PFOA$_t$, the predicted serum concentrations are higher than the measured values in serum for all spatial clusters (example for Zwijndrecht in Figure 17, other figures in the full report). The predicted serum concentrations for the ‘Chicken coop 2 eggs’ scenario (only Burcht) fall within the 95% confidence interval of measured average serum concentrations. The impact of a vegetable garden on predicted serum PFOA concentrations is large. A potential explanation for the exceedance of the predictions for scenario's involving vegetable garden is that the defaults for amounts and frequency of consumption of home grown vegetables are (much) higher than actual consumption amounts and frequencies of the teenagers participating in the HBM study.

Comparing the left and right panel of Figure 17 shows that the predicted and measured serum levels for $PFOA_t$ are much lower than for $PFOS_t$. For Kallo, Burcht and Antwerp the predicted serum levels for $PFOA_t$ for the scenario 'Ornamental garden' are in the same order of magnitude as living in an uncontaminated area. For Burcht, the predicted $PFOA_t$ serum levels for the 'Chicken coop 2 eggs' scenario are also in the same order of magnitude as living in an uncontaminated area, and the predicted serum values for the 15-year-olds match reasonably well with the measured values in serum.

Regulatory relevance of case study outcome: This study confirmed the validity and necessity of the advice to not eat locally grown eggs, and to limit consumption of home-grown vegetables in the vicinity of the 3M plant in Zwijndrecht, which remains important for both $PFOS_t$ and $PFOA_t$.

3.1.1.2.3 Prediction of external exposure to PFAS in contaminated sites in Wallonia, Belgium (ISSeP)

The case study on PFAS hotspots in Wallonia (Belgium) aimed to investigate most suitable models to predict external exposure to PFAS in and around home for the many PFAS affected sites with only a limited set of data (e.g. soil and groundwater concentrations). Among PFAS risk locations related to industrial, military or firefighting activities in Wallonia, the region of Chièvres has emerged as one of the priority areas following recent revelations of PFAS contamination of drinking water. In this region, the drinking water distributed between October 2021 and March 2023 in the municipalities served by the Chièvres water tower contained PFAS in quantities exceeding the future standard of 100 ng/l for PFAS-20 (which will come into force no later than January 12, 2026). The purpose of the study was to identify where/what the contamination sources were, evaluate the environmental contamination in these areas and quantify the external human exposure to PFAS (i.e., with S-RISK) and its several sources and routes. A tiered approach was followed and consisted in tier 1: surface and groundwater, drinking water; tier 2: soils (from vegetable gardens) and tier 3: homegrown vegetables, local eggs and fishes. Moreover, biological data have been collected from an extensive human biomonitoring survey (BMH-PFAS) targeting areas where local populations were exposed to contaminated drinking water (ISSeP, 2024, under review). Therefore, external exposure evaluation could also be further compared with internal exposure through biokinetic/pbpk models.

Due to an unfortunate combination of (i) the (tiered) design of the study, (ii) the limited participation from the local population for soil sampling and (iii) delays inherent to complex decision-making process involving multiple partners and authorities around the PFAS crisis in Wallonia, the case study proposed in Y3 could not proceed as expected. The media coverage of the PFAS crisis in Wallonia greatly complicated the design stage of the scientific projects, which had to be revised and validated by several scientific and political bodies, particularly as regards the legal, financial and communication aspects. Environmental measurements in surface waters, groundwaters and wastewaters have been achieved and corroborated suspicions of contamination due to firefighting management from the military airport of Chièvres. However, no local food samples and a very limited number of soil samples could be collected, that are relevant to human exposure assessment. Even if more data on soils are expected in the few next months, most of those acquired showed PFAS levels in the range or below LOQ, hence, probably not meaningful for the high biological levels measured in these hotspot communities in comparison to drinking water. Subsequent PARC activities related to PFAS hotspot in Wallonia will focus in an in-depth analysis of serum PFAS concentrations measured in Walloon hotspot populations (n=1750 individuals) relying on PFAS-contaminated drinking water, using PARC newly developed PBPK models for PFAS. Predicted serum PFAS levels, will be compared to measured ones and will bring insights into how exposed populations respond to a transient multistage decrease in PFAS contamination from drinking water. The purpose is to provide stakeholders with operational and scientific knowledge to ensure the best post-management public health strategies for these communities.

3.1.2 Indoor environment source-to-dose case studies

Case studies indoor environment were also selected based on regulatory questions, i.e. related to plasticizer from indoor sources, and Pb from premise plumbing systems.

3.1.2.1.1Indoor exposure to plasticizers (CSTB, RIVM, IVL, Unisanté, LNS)

Regulatory questions: The European market has undergone significant changes due to regulatory and market pressures relating to content of phthalates in products. Due to the phthalates' potential adverse effects on human health—such as endocrine disruption and reproductive toxicity—phthalates have been the subject of strict regulatory measures in the European Union (EU). Under the EU's REACH (Registration, Evaluation, Authorisation, and Restriction of Chemicals) Regulation, several phthalates have been classified as Substances of Very High Concern (SVHC) due to their toxic effects. These substances are listed in Annex XIV (Authorisation List), which means that their use requires prior authorization. Companies must demonstrate that the risks associated with these chemicals are adequately controlled or that suitable alternatives are not available. Phthalates that require authorization under Annex XIV include: DEHP, butyl benzyl phthalate (BBzP), dibutyl phthalate (DnBP), and diisobutyl phthalate (DiBP). Additionally, the restriction process under REACH (Annex XVII) limits the use of these phthalates in consumer products. As of July 2020, DEHP, BBzP, DnBP, and DiBP have been banned in concentrations above 0.1 % in articles placed on the market, unless an exemption applies. This restriction covers toys, childcare products, and other goods that consumers come into direct contact with. Beyond REACH, phthalates are regulated under various sector-specific laws, such as the Toy Safety Directive (2009/48/EC), the Medical Devices Regulation (MDR 2017/745), the Cosmetic Products Regulation (EC 1223/2009), and the Waste Framework Directive. The regulation of plasticizers in the EU is constantly evolving, aiming to ensure better protection of human health and the environment.

Scientific questions: Phthalates and non-phthalate plasticizers are considered semivolatile organic compounds (SVOC) due to their oily appearance and low volatility. Once emitted into the indoor air from source materials, plasticizers can be adsorbed onto indoor surfaces and settled dust (Wei et al. 2025). The direct transfer of plasticizers (and other SVOCs) from a source into the dust settled on the source surface is an alternative pathway that increases their final concentration in dust (Ioannis Liagkouridis et al. 2017; Sukiene et al. 2017). These possible pathways lead to inhalation, dermal contact, and ingestion of dust among building occupants, particularly among children. Comprehensive indoor source-to-dose modeling frameworks have been developed in recent years to establish a connection between source emissions and indoor exposure for the general population (Eichler et al. 2021, 2022). Nevertheless, a state-of-the-art review of indoor source and concentration data in the European context is needed to define the scope of current indoor plasticizer exposure and identify research gaps for future data acquisition.

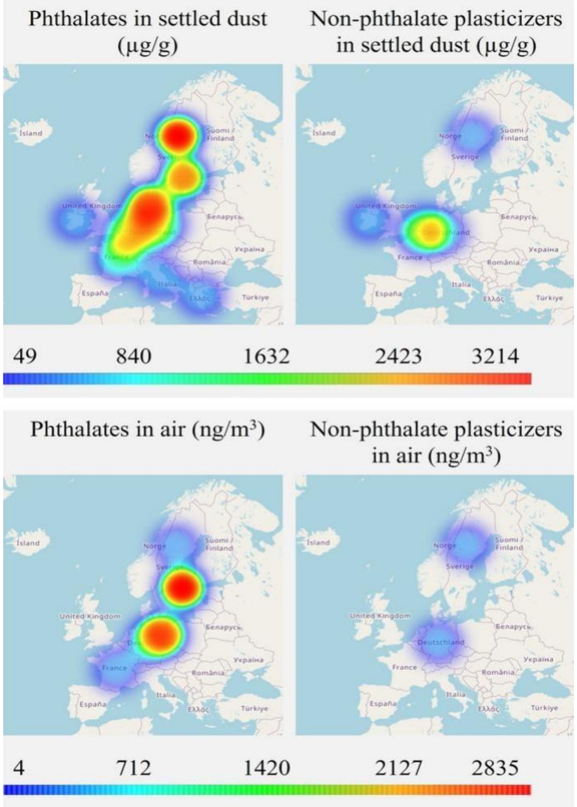
Societal questions: According to statistics from the Organisation for Economic Co-operation and Development (OECD), Europeans allocate approximately 60 % of their daily time to domestic activities and 25 % to professional pursuits (Wei et al. 2025). Consequently, indoor environmental exposure is a major contributor to the overall exposure in the general population.

In Europe, over 1.3 million tonnes of plasticizers are used annually (based on data reported in 2017), with >90 % of plasticizers used for flexible polyvinyl chloride (PVC), and applications ranging from electric cable sheathing to flooring and roofing membranes (Wei et al. 2025). While ortho-phthalates remain the most widely used plasticizers, terephthalates and cyclohexanoates are gaining market share (Wei et al. 2025). Despite the European shift towards alternatives, di-2-ethylhexyl phthalate (DEHP), a widely used orthophthalate, still accounts for 40 % of global plasticizer consumption, particularly in Asia, the Middle East, and Latin America, and may still enter the European market through imports (Wei et al. 2025).

3.1.2.1.2 Plasticizer sources and concentrations in indoor environments: a data overview

The main scope of 6.2.1.a is on (predictive) modelling, however, monitoring data have also an essential role, both as input data, and verification of model predictions. Therefore, it was decided first to collect data on plasticizers in indoor environments (which is for use in the next part of the case study focused on modelling)

We conducted a literature review that aimed to provide an overview of the research on plasticizers in indoor environments (Wei et al. 2025). The review focused on characterizing indoor plasticizer concentrations in gas and sorbed phases and identifying key sources of emissions. We examined existing studies to determine common sampling locations, studied matrices, and source materials. Additionally, the study explored temporal trends in plasticizer concentrations indoors and aimed to build a comprehensive data inventory for future assessment of plasticizer exposure. Phthalates were the most studied plasticizers in indoor air, dust and sources in Europe (Wei et al. 2025).


Phthalates in settled dust (μg/g)

Non-phthalate plasticizers in settled dust (μg/g)

Phthalates in air (ng/m³)

Non-phthalate plasticizers in air (ng/m³)

Figure 18. Graphical overview of the available data on plasticizer exposure in the indoor environment in Europe. Color gradients reflect the concentration distributions in air (ng.m^{-3}) and dust (μg.g^{-1}).

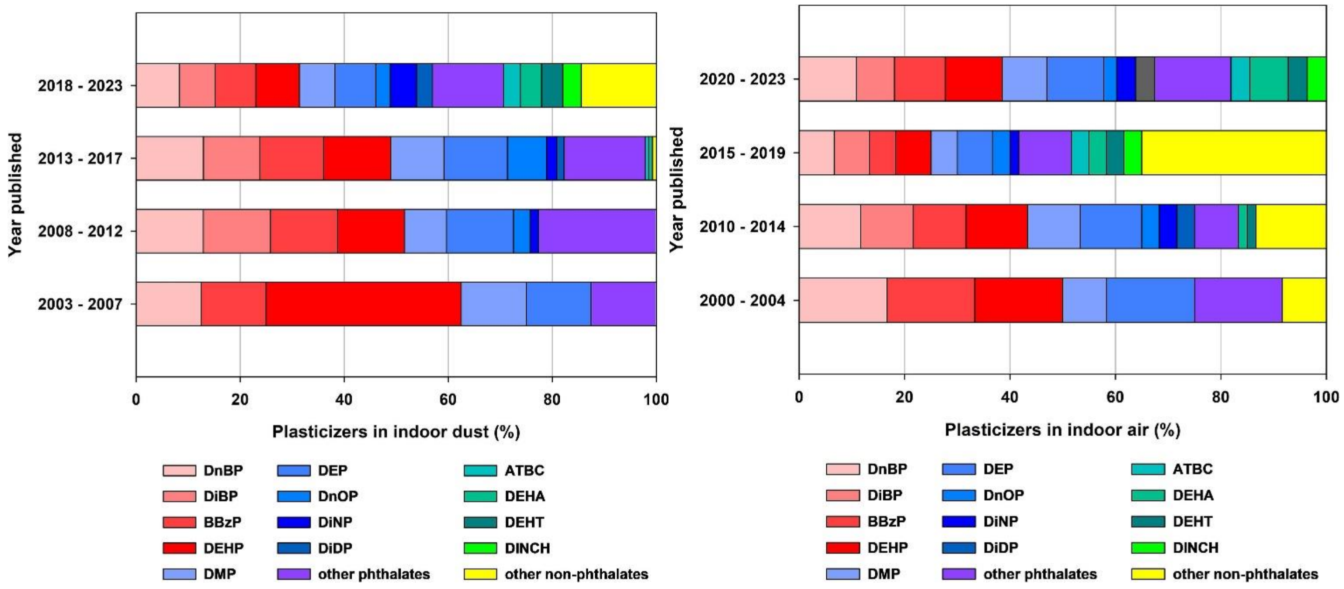
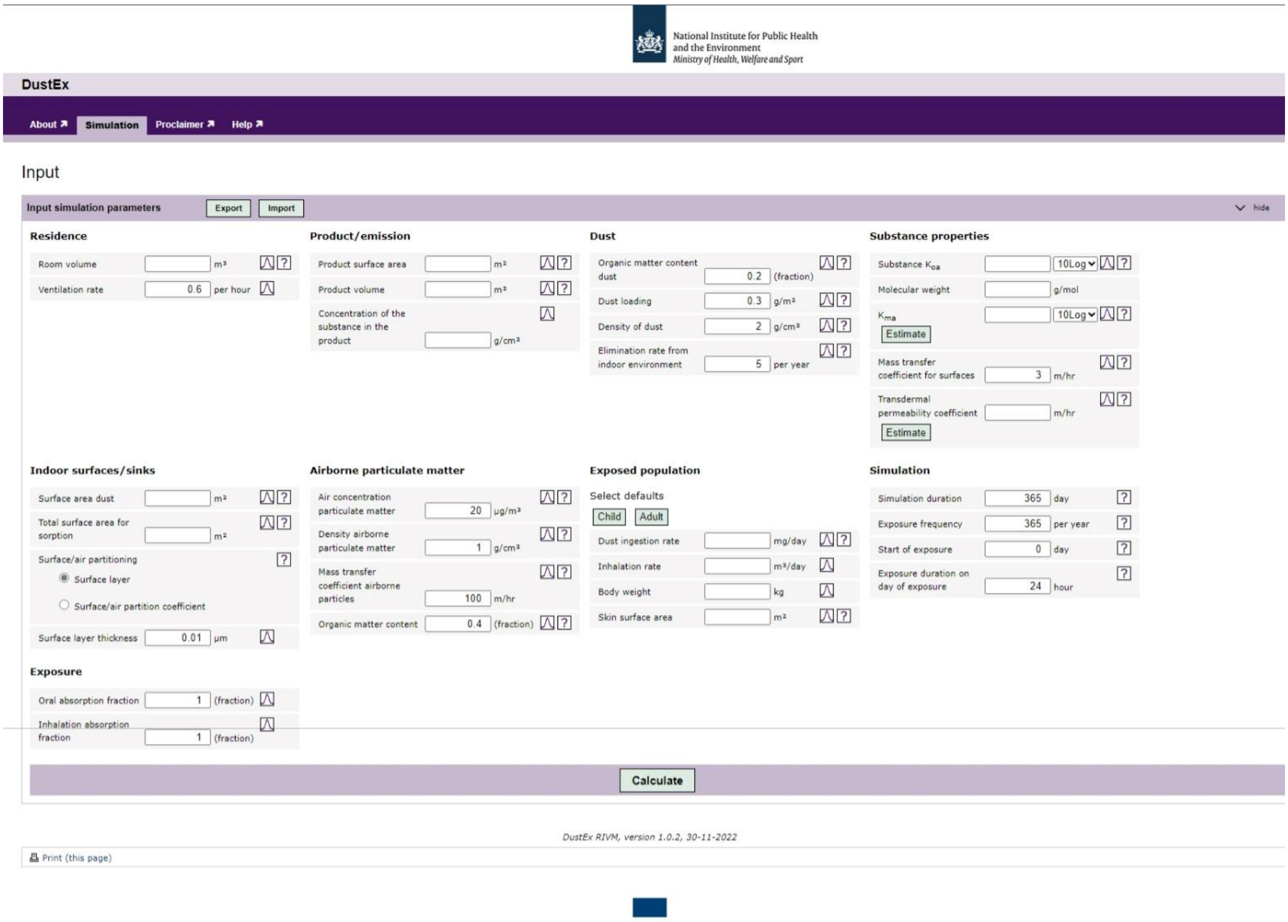


Figure 19. Time trend of plasticizers measured in indoor settled dust (left) and air (right) according to the year of publication.

DEHP has the highest concentrations among other phthalates in indoor settled dust, although we observe a trend of decreasing concentrations. Nevertheless, non-phthalate plasticizers, such as DEHA, DEHT, and DINCH, have been measured more frequently in the indoor environment with a possible increase in concentrations, specifically DEHT, over the past years. It should be noted that repeated observations in the same regions are needed for most plasticizers to establish the trends, which would be useful to demonstrate the success of the EU regulation and restrictions, as in the case of DEHP, but also to evaluate which plasticizers are emerging and require further attention. Residential buildings have been the most studied indoor environment, and settled dust has been the most common matrix for assessing indoor concentrations and exposure. Measurements of indoor source materials have mainly focused on phthalate emissions from vinyl flooring, while the emission characteristics of other plasticizers from different plastic products have not been well-assessed. The present work highlights the influence of European regulations on indoor plasticizer trends, showing a decrease in the concentration of old phthalates and an increase in emerging alternatives. Sampling and analytical methods for future field studies and emission tests need to be adapted to improve the detection of these alternatives. For future developments in indoor plasticizer source diagnostics and exposure assessments, the present work highlights the need to enrich the source emission and indoor concentration data in Europe, specifically for non-phthalate plasticizers, and to establish a connection between the source materials and the indoor matrices for better risk management.

3.1.2.1.3 Indoor environmental concentrations of plasticizers and other semi-volatile organic compounds: comparing predictions of different models with each other and with measurements

RIVM - DustEx model: RIVM, together with ETH Zürich (ETHZ) and the Swiss Federal Laboratories for Materials Science and Technology (EMPA), has previously developed the DustEx model for estimating exposure to semi-volatile organic chemicals (SVOCs) from consumer articles. DustEx dynamically models the entire pathway of SVOC exposure, from the release of SVOCs from the consumer articles to consumer exposure. SVOC concentrations in the product, the gas-phase air, airborne particles, and settled dust, and on sorptive surfaces, are tracked through time in parallel with the exposure through inhalation of gas-phase air and airborne partciles, ingestion of settled dust, and dermal absorption from air. DustEx was originally implemented by RIVM, ETHZ, and EMPA in R, and has subsequently been made available via a free to use web interface (https://dustex.nl/, see Figure 20).



Residence

Room volume: m³

Ventilation rate: 0.6 per hour

Product/emission

Product surface area: m²

Product volume: m³

Concentration of the substance in the product: g/cm³

Dust

Organic matter content dust: 0.2 (fraction)

Dust loading: 0.3 g/m²

Density of dust: 2 g/cm³

Elimination rate from indoor environment: 5 per year

Substance properties

Substance K_{oa}: 10Log

Molecular weight: g/mol

K_{ma}: 10Log

Mass transfer coefficient for surfaces: 3 m/hr

Transdermal permeability coefficient: m/hr

Indoor surfaces/sinks

Surface area dust: m²

Total surface area for sorption: m²

Surface/air partitioning

● Surface layer

○ Surface/air partition coefficient

Surface layer thickness: 0.01 μm

Airborne particulate matter

Air concentration particulate matter: 20 μg/m³

Density airborne particulate matter: 1 g/cm³

Mass transfer coefficient airborne particles: 100 m/hr

Organic matter content: 0.4 (fraction)

Exposed population

Select defaults

Dust ingestion rate: mg/day

Inhalation rate: m³/day

Body weight: kg

Skin surface area: m²

Simulation

Simulation duration: 365 day

Exposure frequency: 365 per year

Start of exposure: 0 day

Exposure duration on day of exposure: 24 hour

Exposure

Oral absorption fraction: 1 (fraction)

Inhalation absorption fraction: 1 (fraction)

DustEx RIVM, version 1.0.2, 30-11-2022

Figure 20. The web interface of DustEx.

To evaluate the performance of DustEx, Sukiene et al. 2016, 2017 have followed concentrations of several plasticizers over time in a controlled residential field study. In this study, plastic products doped with deuterium-labelled plasticizers were introduced in occupied Swiss apartments. The plasticizer concentrations were measured at the start and end of the measurement campaigns in the artificial products, and at intervals throughout the campaigns in the air and settled dust. Previous efforts to model the experimental results with DustEx were, however, unsuccessful because the mass balance could not be closed.

In this case study, we improved the modelling of Sukiene's experiments with DustEx using new techniques based on Bayesian statistics. Measurements below the limit of detection were taken into account by using a tobit likelihood (Tobin 1958) function (see Figure 21). The model parameters were given log-normally distributed priors centered on the value believed to be most likely, but with an allowance for deviation. The resulting Bayesian posterior is designed to find a trade-off between the best fit to the experimental data and the most reasonable parameter values. The parameter space is explored with nested sampling (Skilling 2006), a Monte Carlo technique that provides more robust results than a Monte Carlo Markov chain (MCMC).

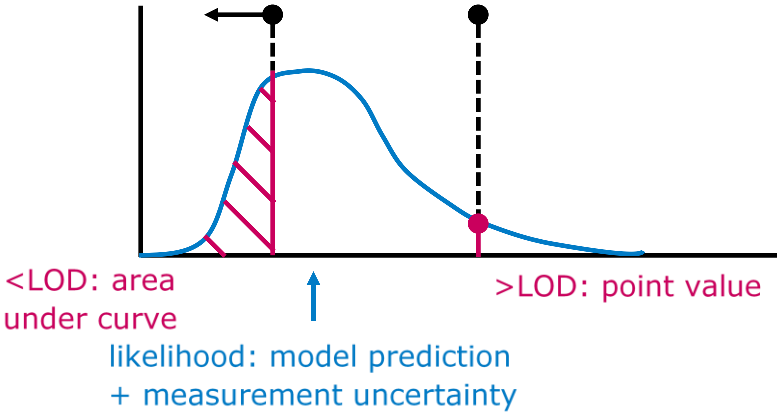


Figure 21. An illustration of tobit likelihood functions. The horizontal axis depicts the measured parameter, the vertical axis shows the probability that such a parameter value is observed. The probability is based on the prediction of the model in combination with measurement uncertainties. Depending on whether the measured value is under or above the limit of detection (LOD), the likelihood of observing that value is calculated either as the area under the curve (<LOD) or as a point value of the likelihood function (>LOD). The calculated likelihood is combined with the prior probability of the model parameters to give the posterior probability. The goal is then to find the model parameters for which the posterior probability is maximal, which is the best compromise between goodness of fit and parameter credibility.

This method was applied to the case of the plasticizer DEHA in Apartment 5. The results indicate that the products deplete much faster than predicted from lab measurements, and that extra sinks or stronger sinks are required to explain where the majority of released plasticizer has gone. We have considered additional sink surfaces, an underestimated ventilation rate, and the inclusion of airborne particles in the ventilation, but none could by itself explain the measurements. An example of constraints found on model parameters in one of the runs in given in Figure 22.

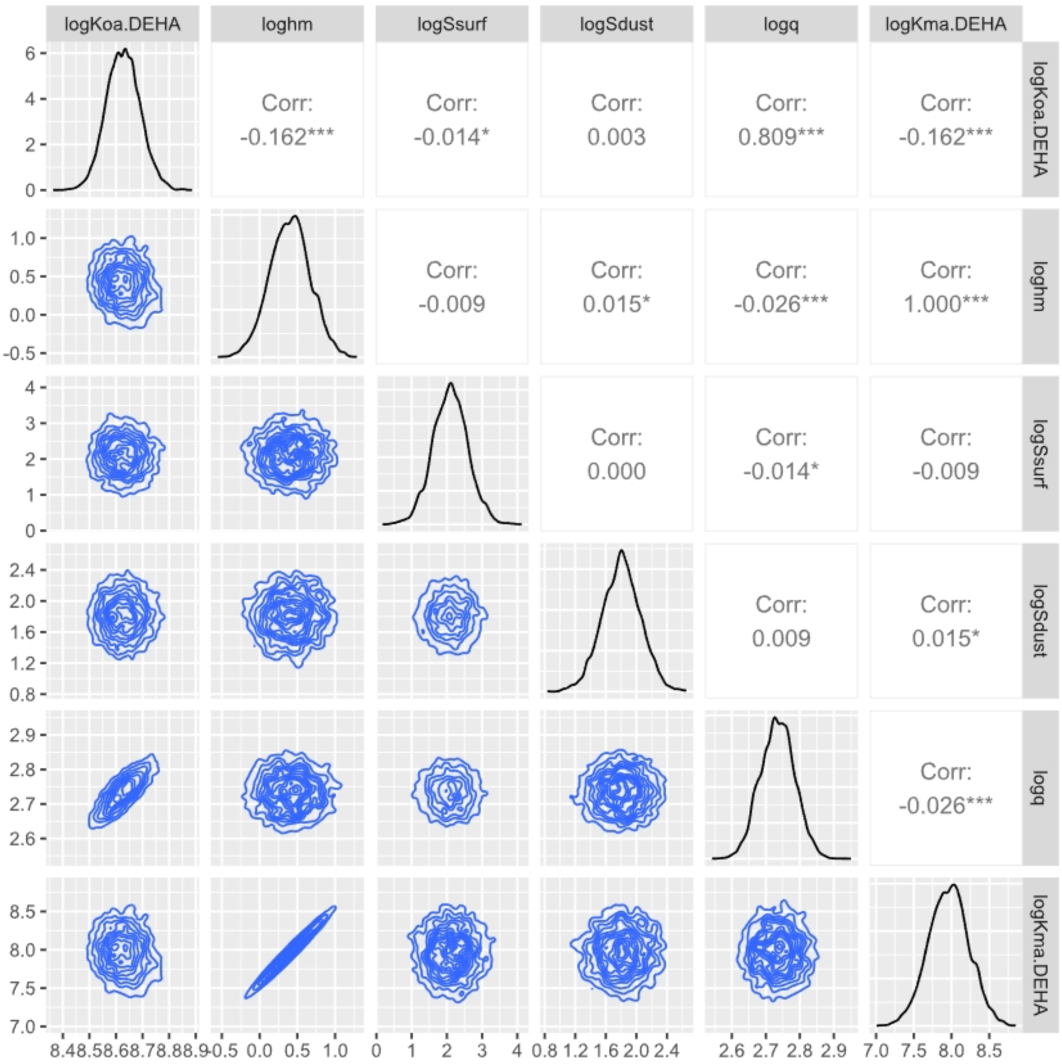


Figure 22. An example of DustEx model parameter constraints, while trying to reproduce the DEHA concentrations in Apartment 5 of the Sukiene studies. The parameters are all measured as base-10 logarithms, and are from left to right: octanol-air partition coefficient of DEHA (unitless), mass transfer rate (m/h), area of sorbtive surfaces (m^2), area of settled dust (m^2), ventilation (air changes per hour), and material-air partition coefficient of DEHA (unitless). In this run, looser priors were given to the area of sorbtive surfaces and the ventilation rate, than to the area of settled dust. Consequently, the model tries to close the mass balance by increasing the area of sorbtive surfaces and the ventilation rate to unrealistically high values.

CSTB – MOMIX model: The SVOC model developed at CSTB (Figure 23) was previously validated using measurement data obtained from a test house in the US for BBzP and DEHP (Bi, Liang, and Xu 2015). In this case study, we tested DEHA and DiBP compounds using the data obtained by Sukiene et al. The measurements were conducted in 5 unoccupied apartments. The experimental and calculated indoor concentrations of DEHA and DiBP differed by an average of 41% and 57%, respectively. These differences can be explained by two assumptions applied in the case study. First, the SVOC emission rate was assumed to be linearly correlated with its content in the source materials, with the initial SVOC content depleting over time. Second, the air change rate was assumed to be constant based on a single measurement. This case study highlights the importance of determining the source emission and monitoring the ventilation rate for future indoor measurement and modeling studies.

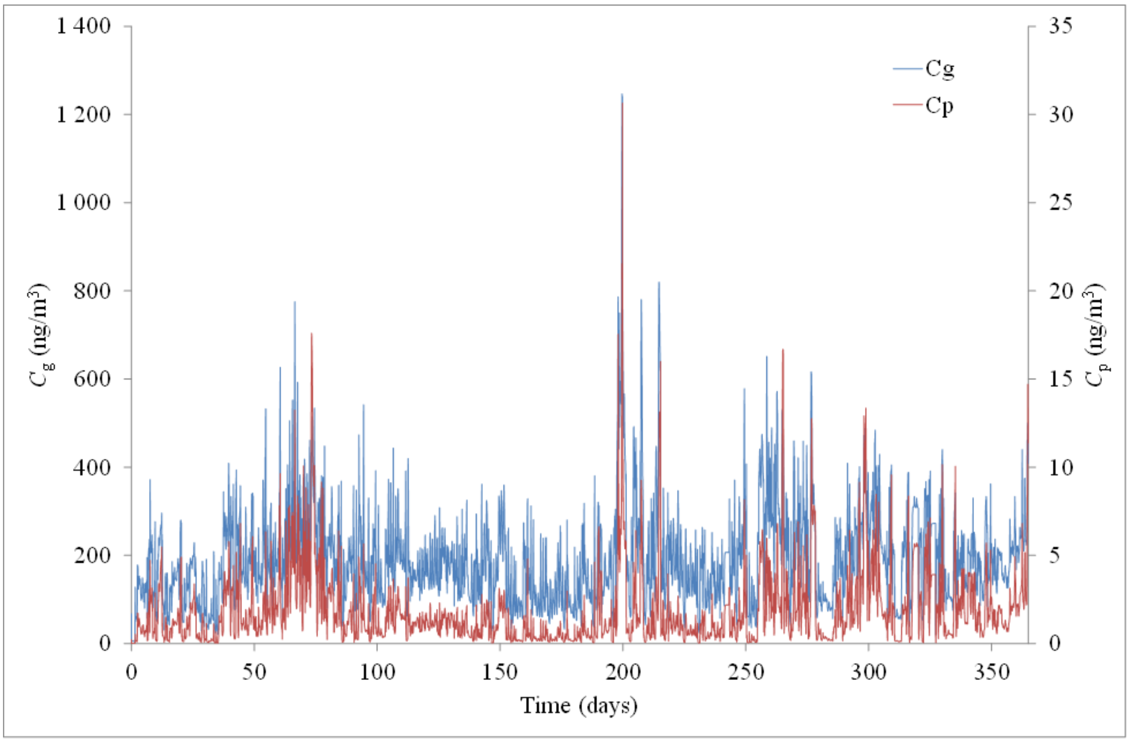


Figure 23. Data format of the output of CSTB SVOC model (C_g: concentration in gas phase; C_p: concentration in particle phase).

IVL - Indoor SMURF model: An experimental dataset consisting of measured air and dust concentrations of plasticizers (i.e. ATBC, DINCH, DINP and DEHP) as well as their corresponding levels in the flooring material (assumed as the main source) in Swedish preschools has been used to investigate the relationships between the emission source strength and indoor air and dust levels. In 1 out of the 3 studied school environments indoor sampling was performed soon after the construction was completed and a new flooring had been installed containing the plasticizer. In this preschool, a follow-up sampling was performed 1 year after construction.

The indoor SMURF model (I. Liagkouridis et al. 2017), a fugacity-based steady-state indoor fate model has been used in this case study. The model can predict SVOC concentrations in various indoor environmental compartments i.e., air (gas and particle phases), horizontal and vertical surfaces, floor dust, organic film etc. based on a given emission into the air input. It has also been retrofitted so it can back-calculate the emission intensity from both the air and dust concentrations allowing for the identification of an emission-to-dust signal. For the purpose of this study, the model was expanded by including a source emission module that allows for the estimation of SVOC emissions from a product/material source based on established approaches (Eichler and Little 2020).

Application of the model in the newly built preschool resulted to a large overprediction of both air and dust concentrations (between 2-3 and 1-2 orders of magnitude for air and dust, respectively) when compared to the measured data directly after construction (Figure 24a). Although this may be partly due to input parameter and model uncertainty as well as measurement uncertainty, it is suggested that the large discrepancy is mainly a result of the indoor system not having reached steady-state with regard to the plasticizer (ATBC) emissions from the flooring material. This became more evident when modelling results were compared to the measured data from the follow-up sampling (1-year later) that revealed a lower emission strength (much of the ATBC in the flooring had been depleted) and elevated levels in air and dust. In that case model and experimental showed a better agreement (a factor of 4 for air and 2 for dust concentrations, respectively, see Figure 24a) indicating that the system is close to steady-state. That was the case for the second preschool also (not newly constructed) where model and measured data for DINCH levels in the air agreed very well for air concentrations while an overprediction of dust levels by the model was observed (Figure 24a). Consistent with the latter observation, a back-calculation of the emission strength based on both air and dust concentrations revealed consistently higher dust-based than air-based emissions (Figure 24b) indicating the existence of dust-mediated emission pathway (i.e., source-to-dust in direct contact and material abrasion) that leads to higher plasticizer loads in dust than accounted by air-mediated transfer.

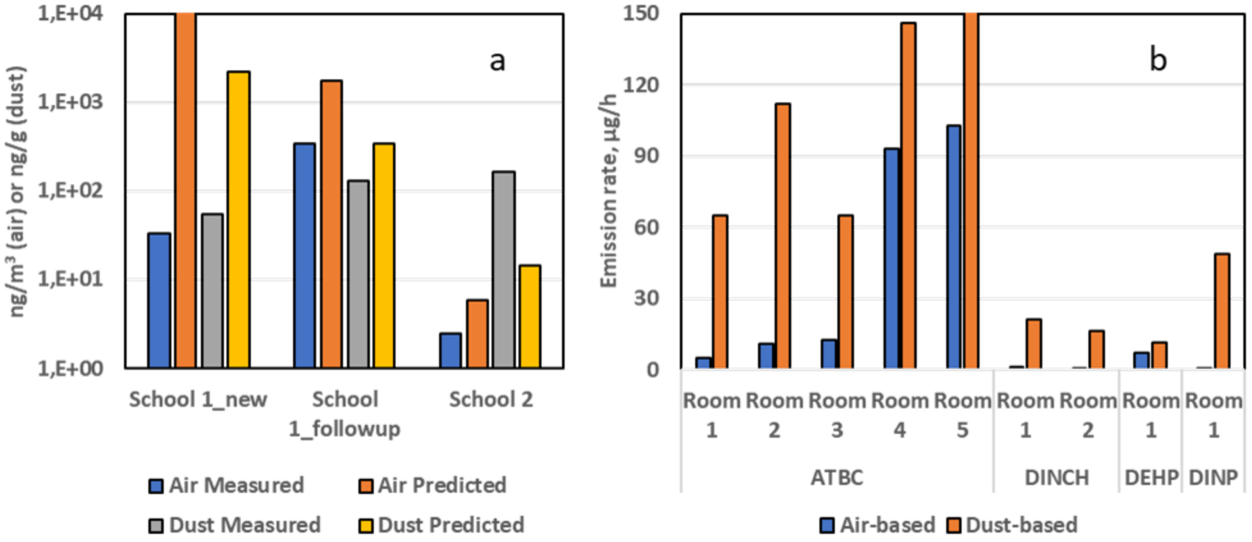


Figure 24. a) Measured vs indoor SMURF modelled air & dust concentrations, and b) air-based vs dust-based modelled emissions for the different school microenvironments.

3.1.2.1.4Ongoing case study (indoor air and dust)

Following the benchmarking of the three indoor source-to-dose models (described in the above 3 case studies) and the improvement of data harmonization, model reliability, and model interoperability as mentioned in the previous section, the ongoing case study aims to establish a simulation chain to bridge the gap between source emission, concentration, and exposure in the indoor environment. Plasticizers were chosen for the pilot study, because common databases of plasticizer concentrations from field studies were available for model parameterization and simulation. The objectives of the case study include: 1) indoor source identification and characterization based on concentrations in different building types and 2) indoor environmental exposure assessment. The case study will be finalized, and the results will be published by the end of the 6.2.1a Source-to-dose project period, which is foreseen for November 2025.

3.1.2.1.5Modelling lead exposure source via drinking water caused by components in premise plumbing systems (KWR)

Regulatory questions: The norm for lead in drinking water was recently reduced from 10 to 5 µg/L (European Parliament and Council 2020). From a regulatory perspective, questions arise such as: how can we unearth sources of lead in drinking water on a large-scale, who is to be kept accountable, and how should accountability be enforced?

Scientific questions: From a scientific perspective, questions arise such as: how can the complex interplay between plumbing system geometry, stochastic water demand, and time-dependent lead leaching be captured in a model, how trustworthy is such a model, what insights does such a model give about real-world measurements, what is needed to extend such a detailed model to gain insights at the population level?

Societal questions: From a societal perspective, questions arise such as: how can citizens be stimulated to investigate their plumbing systems, how can citizens be made more aware of their choices in the plumbing system?

Description of case study (context/situation): This case study focuses on the oral route and source of exposure to lead via drinking water. The case study can be described with the following question: for a household with a given premise plumbing geometry, water consumption characteristics, lead leaching components located at a specific spot with specific leaching characteristics, what is the lead concentration in drinking water at the tap? The results shown here are a condensed version of a research report commissioned by the Dutch drinking water sector (Dash, Galama-Tirtamarina, et al. 2024).

The case study involves studying a single typical (though fictious) home occupied by two adults. The case study is oriented towards the Dutch scenario based on the inputs to the model. The scope can be broadened towards a larger population by performing an extended sensitivity analysis through an introduction in variation in all the input parameters, field data for which is not readily available.

Such a detailed model also offers more clarity than real-world measurements. Figure 25 shows how drinking water demand varies in time, in a typical household. This temporal variation of water usage across the plumbing system determines how much lead leaches into the system and where it flows to. As a consequence, there is considerable variation in lead concentration at the tap. The shortcomings of real-world measurements (incomplete view of the true situation) is circumvented by the model.

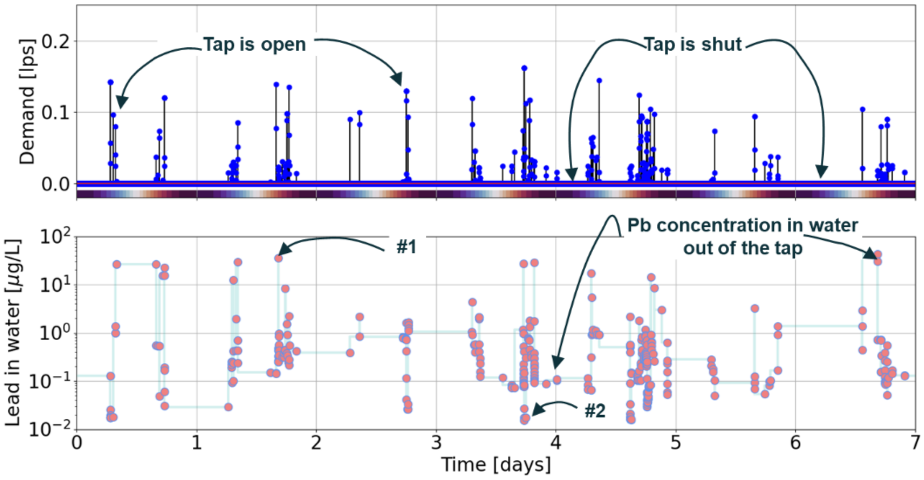


Figure 25. Lead concentrations at the tap fluctuate wildly in time. Real world measurements capture a snapshot which may or may not reflect the true situation. These graphs display typical results from simulations. The graph on top shows moments at which a tap has been opened in the simulation and the graph on the bottom shows the lead concentration in the water out of the tap at the moments when the tap is open. The lead concentration at moments #1 and #2 are much higher and lower, respectively, than the average concentration over the entire week.

Modelling approach: The modelling framework is called LEadGO and is comprised of three key ingredients:

- The plumbing system (lengths/diameters of pipes and location of various consumption points).
- The water consumption time series (dependent on the number of inhabitants and their behaviour).
- The location and characteristics of lead leaching (characterized by plumbosolvency and a timescale for how quickly the equilibrium value is reached).

The lead concentration at the tap is dependent on the interplay between the three ingredients. The models are run using python, and the package WNTR (Klise et al. 2017) forms the backbone for all the calculations.

Input data: LEadGO requires the following input data:

- An EPANET INP file which contains the geometry of the plumbing system.
- Water demand patterns generated using SIMDEUM (Blokker, Vreeburg, and van Dijk 2010), attached to the plumbing system.
- The location of lead leaching components and lead leaching characteristics.

In the present study, a typical Dutch single-family residence is considered as a basis for the plumbing geometry (a premise spread out over three storeys). The water demand patterns are based on average water consumption behaviour for a Dutch household with two adults. The location/characteristics of lead leaching are based on actual laboratory experiments on components found in Dutch plumbing. It is assumed that the incoming water from the distribution network is free of lead, which is a reasonable assumption for the Dutch drinking water network.

Model output, results, verification/validation and discussion: LEadGO gives several outputs such as pressure, flow velocity, and lead concentration across the plumbing system as a function of time (with a resolution of ten seconds). A typical output of the simulation is visible in the lower part of Figure 25 – lead concentrations at a tap with a resolution of ten seconds across a week. In this study, we focus primarily on the average lead concentration across all twenty weeks of unique water demand patterns. A time average lead concentration over a longer period is mainly relevant given the main concern for health effects following chronic exposure to lead. The modelling framework was validated with experiments (experiments performed outside the framework and funding of PARC). Details of experiments can be found elsewhere (Dash, Galama-Tirtamarina, et al. 2024).

The modelling framework was applied to various informed scenarios. Here, we consider only six examples for brevity. The six examples that are considered here have three combinations of the location of lead leaching (shutoff valve, water meter or kitchen faucet) and the characteristics of lead leaching for two material types (brass CW602 and brass CW617). These two materials are not allowed following the recent update to the European Positive List of materials in contact with drinking water. However, these may be found in existing installations. The brass CW602 contains 1.7-2.8% lead by weight whereas brass CW617 contains 1.6-2.2% lead by weight. The equilibrium lead concentration, E, for CW602 and CW617 is measured to be 223.7 µg/L and 19.3 µg/L respectively. The leaching rates, M, are measured to be 0.014 $\mu g/(m^2 \cdot s)$ for both CW602 and CW617. These values are based on specimens for which stagnation tests were performed. The timescale, T, for dissolution for a pipe is dependent on these two parameters and the diameter, D, and can be derived with $T = DE/(4M)$.

We focus in our case study at the results of lead concentrations in water coming out the kitchen tap, as this is the most often used tap for oral consumption. Brass in the shutoff valve and water meter do not lead to an exceedance of the (new) norm of 5 µg/L, irrespective of the type of brass. When the brass is at the kitchen faucet, the average lead concentration at the tap shoots up, despite the much lower volume contaminated water (16 ml vs 160 ml for the shutoff valve and water meter). For this case, it does matter which kind of brass is utilized. The use of brass CW602 at the kitchen faucet leads to an exceedance of the norm. This shows that when it comes to lead leaching in the plumbing system, location matters. In fact, the presence of a lead-releasing component in the final branch of the plumbing system towards the kitchen faucet is the least desirable situation (Dash, Galama-Tirtamarina, et al. 2024).

Regulatory relevance of case study outcome: The following aspects from the case study are relevant from a regulatory perspective:

- The norm of 5 µg/L is typically tested with the random day-time sampling where a liter of water is collected at a random moment. As explained in Figure 25, such a snapshot may not provide information about the reality. In order to locate components that conducts to lead exceedance, a different sampling procedure would be required.
- The norm of 5 µg/L is based on an 'as low as reasonably possible' principle. It is, thus, important to locate as many lead pipes hidden behind the walls of hundreds of thousands of homes across Europe (Baron et al. 1995). The profile sampling technique can provide important insights into the presence and location of the lead releasing components (Dash, Blokker, et al. 2024; Dash, van Steen, and Blokker 2024; Triantafyllidou et al. 2021). By localizing the lead releasing component, it makes it evident which party, the drinking water utility or the premise owner, is responsible for removing the lead.
- The case studies show that the presence of brass components in the assets of the drinking water utility (shutoff valve and water meter) are unlikely to lead to norm exceedance. Drinking water utilities have concluded that they can stick to their current replacement strategy.
- The presence of lead-releasing components in the final branches of the plumbing system are the least desirable situations. The premise owner is responsible for the water quality in this domain, i.e. individual consumers who may be less aware as compared to a centralized entity such as a drinking water utility.

Transferability of case study outcome: The modelling framework can be applied in various other ways as explained below.

Situations: While the inputs of this study considered a typical Dutch household (in terms of plumbing system and water consumption behaviour), this may be easily extended to scenarios typical for other countries.

Substances: This modelling framework can be extended to other substances that leach from the (pipe) wall in the plumbing system. LEadGO can also be trivially used to study mixtures, as long as the individual substances do not interact with each other.

External to internal exposure: The results of simulations from this modelling framework can serve as a starting point to evaluate blood lead levels using PBPK models for lead (in collaboration with T6.2.2). It is worthwhile exploring whether the outputs of this model can be used in A6.2.2 to quantify internal exposure (since lead uptake in human body will also have a timescale).

PARC toolbox: The modelling framework considered here is being made available via the PARC toolbox. This is done by integrating the python scripts into a Jupyter notebook. Such a Jupyter notebook can serve as a low barrier-to-entry to understanding/using this intricate model by a broader set of researchers. Using the tool, however, does require a certain degree of proficiency in python, creating the input files on EPANET, and understanding drinking water consumption.

3.2 General and Occupational environments for Aggregate Exposure

The methodological developments proposed in the section 2.2 as well as the output of the model selection from section 2.3 were used as a starting point to develop the case studies for aggregate exposure. At this stage, exposure modelling/scenario for the general and occupational environments were developed separately and by prioritized chemical families (PFAS, cadmium and chromium for metals, plasticizers and pyrethroids). Several working groups were launched: WG PFAS consumer products, WG PFAS general environment, WG PFAS occupational environment, WG Cadmium in consumer products, WG Cadmium general environment, WG Cadmium and chromium occupational environment WG Pyrethroids occupational environment, WG Plasticisers occupational environment. To ensure consistency and connection between case studies Project leaders and case study leaders participated in both general and occupational environments meetings. For general environments, after defining common approaches, exposure models, data (ex: European database for PFAS and Cadmium), each partners started application to their own countries data.

Table 3 and Table 4 gives an overview of the progress made by each partner. As the development of the PARC model network was conducted in parallel to implement exposure and PBK models needed for the case studies, partners started to use their own model or preliminary version of common models under R programs. The sections below summarizing the progress made by each partner for the general populations and by the occupational working groups to develop occupational exposure scenarios. The year 4 will be consecrated to harmonize the data, models, tools used in the current case studies to be able to provide more harmonized results at European levels and to start to connect general and occupational environments. Interactions with P6.2.2 PBK model project will be also increased in developing transversal working groups.

Table 3. Overview of partners' progress on general environment cadmium and PFAS case studies. X: Done, IP: in progress.

Case	Country	Sources and routes selection	External exposure model selection	Data formatting	External exposure assessment	Lifetime external exposure simulations	Simulation of internal exposure using PBK models	Comparison with HBM data	Harmonisation bewteen countries	Comparison between countries
PFAS	France	X	X	X	IP					
PFAS	Belgium	X	X	IP						
PFAS	Switzerland	X	X	IP						
PFAS	The Netherlands	X	IP	IP	IP					
PFAS	Norway	X								
PFAS	Poland	X								
Cd	France	X	X	X	X	IP	IP			
Cd	Slovenia	X	X	X	IP					
Cd	Belgium	X	X	X	IP					
Cd	Switzerland	X	IP	IP	IP					
Cd	Spain	X								
Cd	Portugal	X								

Table 4. Overview of partners' progress on occupational environment cadmium and PFAS case studies. X: Done, IP: in progress.

Case	Occupation	Exposure scenario	Occupational exposure model selection	External exposure modelling – 1st modeler	External exposure modelling – 2nd modeler	Comparison to air measurements	Combining with general environment	Internal exposure modeling	Comparison with HBM data	Comparison between countries
Cd	Ash removal in power plant boiler	X	X	X	X	IP	IP			
Cd	Maintenance work in power-plant boiler	X	X	X	X	IP	IP			
Cd	Silver-Cadmium soldering	X	X	X	X	No data	IP			
Cd	Manual glass manufacturing	X	X	X	X	X	IP			
Cd	E-waste workers battery recycling	X	X	X	X	X	IP			
CrVI	Chrome plating (all types)	X	X	X	X	IP	IP			
CrVI	Spray painting aircrafts	X	X	IP	X	IP	IP			
CrVI	Welders	X	X	IP	X	IP	IP			
CrVI	Steel factory workers	X	X	X	X	X	IP			
PFAS	Ski waxers	X	X	X	X	X	X	IP	IP	
PFAS	Chrome platers	X	X	X	IP	IP				
PFAS	Fluorochemical plant workers	X	X	X	IP	IP				
PFAS	Firefighters	IP	IP							
Plasticizers	Carpet removal	X	X	X		IP				
Plasticizers	Manufacturing by extrusion	X	X	X		IP				
Plasticizers	E-waste	X	X	IP						
Plasticizers	School teachers	X	IP							

3.2.1 PFAS: General and Occupational environments for Aggregate Exposure

3.2.1.1 Exposure to PFAS from General environment

3.2.1.1.1PFAS, European database on concentrations in consumer products (ANSES, VITO, RIVM, KEMI, IVL, UoB, FOPH, LNS, NIPH, RECETOX)

One major gap identified regarding exposure data was the lack of organized data on the concentrations of chemicals in consumer products at both the national and European levels. To address this, we initiated a literature review to identify consumer products that may contain PFAS, collect data on the percentage of contaminated products, the concentration levels and modelize the collected data with probabilistic distributions that can be used by the different partners in the PFAS case studies.

The literature review enables to identify PFAS-contaminated consumer products, and to gather in a database the quantitative contamination data, particularly for products available in European markets, but international products potentially sold in Europe were also considered. The review spans publications between 2019 and 2024. Various national and international reports were consulted, along with scientific articles, institutional reports, and databases. Opportunistic reference collection was also conducted. Bibliographic query was done in the Scopus database and was based on PECOTS criteria (Population, Exposure, Comparator, Outcome, Timing, and Setting). 1104 references were found, and a total of 1471 were identified after combining with opportunistic searches. References were filtered based on the product type (consumer goods), type of measure (i.e. quantitative), substance measured (i.e. PFAS) and their relevance to the European market. Ultimately 43 references were eligible for data banking. Identified consumer products fall into the following categories: textiles, cosmetics, maintenance and DIY products, ski waxes, paper products, absorbent hygiene products, and baby diapers. The database is available to T6.2.1 partners on the PARC sharepoint. This work is still in progress.

3.2.1.1.2 PFOA, France – General aggregate exposure from food, air, soil, dust, and consumer products (Anses)

Context and issues of PFAS exposure in France: In France, the Esteban study highlighted the presence of perfluorinated compounds in humans. Seven PFAS (PFOA, PFNA, PFDA, PFUnA, PFHxS, PFHpS et PFOS) were quantified at 40% in adults and six in children. PFOA and PFOS were quantified in 100% of people tested (Santé Publique France 2012). The subject of PFASs is regularly in the media headlines, and risk managers are gradually getting to grips with it: for example, in 2022 the Prime Minister commissioned a government mission to update and complete the diagnosis of the situation in France, and to propose a management roadmap for the short, medium and long term (Isaac-Sibille 2024). The report was published in 2024, and recommendation 3 concerns notably the strengthening of work on the exposome, which includes aggregate exposure, with PARC mentioned as the spearhead project. This cannot be achieved without improving our knowledge of the sources of exposure involved and the data available: this matter was referred to Anses in 2023, and involves agents working in PARC-A6.2.1. These factors show the value of carrying out this work in France: improve scientific knowledge in the face of a worrying health situation, and enlighten public decision-makers who have recently taken up the issue.

Input data for the different sources and routes: As a first step, exposure modeling was carried out for PFOA. A review of the sources and exposure data (exposures factors and concentration in sources) was carried out to collect the relevant exposure data to perform aggregate exposure to PFOA in France (Table 5).

Table 5. Summary of input variables used for the calculation of aggregate exposure to PFOA and PFOS for French population.

Source	Routes	Exposure factors and concentration in sources	Stratification variables	References
All.	All.	Body weight (kg).	Sex, Age, Location (French administrative	INCA2; Bebe SFAE 2005.

			regions), Environment of living (rural or urban), Smoking status.	
Diet	Ingestion.	Average daily amount of food item f, $f \in \llbracket 1, F \rrbracket$, consumed by an individual (g.d^{-1}). F total number of food item.	Sex, Age, Location, Environment of living, Smoking status.	INCA2; Bebe SFAE 2005.
Diet	Ingestion.	PFOA concentration in food (µg.g^{-1}).	Location (French administrative regions).	TDS 2, TDS infantile.
Soil	Ingestion.	Average daily amount of soil ingested by an individual (g. d^{-1}).	Age.	USEPA, 2011, EFH; USEPA, 2017, EFH.
Soil	Ingestion.	PFOA concentration in soil (µg.g^{-1}).	Location, Environment of living.	Dauchy et al. 2017.
Dust	Ingestion.	Average daily amount of dust ingested by an individual (g.d^{-1})	Age.	USEPA, 2011, EFH; USEPA, 2017, EFH.
Dust	Ingestion, Dermal.	PFOA concentration in dust (µg.g^{-1}).		Goosey and Harrad 2011
Dust	Dermal.	Fraction of PFOA in dust available for dermal contact (/1).		Bekö, G., et al., 2013, from Vanecker, M., et al., 2020b.
Dust	Dermal.	Amount of dust adhering to the skin (g.m^{-2}).		Bekö, G., et al., 2013, from Vanacker, M., et al., 2020b.
Dust	Dermal.	Time of home dust exposure (h).		Hermant et al., 2017., from Vanacker, M., et al., 2020b.
Dust, Indoor air, outdoor air.	Dermal.	Body surface (m^{-2}).	Sex and age.	USEPA, 2011, EFH.
Dust.	Dermal.	Fraction of the body surface exposed to dust (/1).	Sex.	U.S. EPA, 2011a., from Vanecker, M., et al., 2020b.
Indoor air, outdoor air.	Dermal.	PFOA concentration in indoor air (µg.m^{-3}).	Location.	No data in France. Hypothesis: same value as outdoor air.
Indoor air, outdoor air.	Dermal.	PFOA concentration in outdoor air (µg.m^{-3}).	Location.	Saini et al. 2023
Indoor air, outdoor air.	Dermal.	Fraction of the body surface exposed to air (/1).	Sex.	U.S. EPA, 2011a., from Vanecker, M., et al., 2020b.
Indoor air, outdoor air.	Dermal.	Deposition velocity of airborne particles onto the skin's surface (m.h^{-1}).		Hermant et al., 2017., from Vanecker, M., et al., 2020b.
Indoor air, outdoor air.	Dermal, inhalation.	Fraction of daily time spent indoors (/1).	Age.	USEPA, 2011, EFH.
Air.	Inhalation.	Daily ventilatory flow (m^{3}.d^{-1}).	Sex and age.	INCA 2, from Vanacker, M., et al. 2019 ; and Vanacker, M., et al., 2020.
Cosmetics.	Cosmetics - dependent	Use frequency (d^{-1}).	Age, sex.	PACEM data.
Cosmetics.	Cosmetics - dependent	Use amount (g).	Age, sex.	PACEM data.
Cosmetics.	Cosmetics - dependent	Percentage of products with substance (%).	Age, sex.	RIVM pilot study described in section 3.2.1.1.5. 3.2.1.1.1
Cosmetics.	Cosmetics - dependent	Exposure fraction (dimensionless).	Age, sex.	RIVM pilot study described in section 3.2.1.1.5. 3.2.1.1.1
Cosmetics.	Cosmetics - dependent	PFOA concentration in a cosmetics(µg.g^{-1}).	Age, sex.	RIVM pilot study described in section 3.2.1.1.5. 3.2.1.1.1

Modelling approach for aggregate exposure: In relation to available data described in the previous paragraph, the following exposure source-exposure route pairs were selected: Food-ingestion, Indoor settled dust-ingestion, Indoor settled dust-dermal contact, Soil-dermal contact, Air-dermal contact, Air-inhalation, and cosmetics products exposure (as a first step RIVM pilot study, see Netherlands section for details).

The model selection process mentioned in section 2.4.1 was used. RSExpo emerged as the most relevant tool for the different sources-routes, except for cosmetics, where PACEM (Delmaar et al. 2024) was used. RSExpo is based on the equations described in Vanacker, Quindroit, et al. 2020b and Vanacker, Tressou, et al. 2020.

Simulation of internal concentrations in urine: Initially, average daily *PFOA* flows were calculated using absorption factors for internal exposure. In the remainder of the project, it is planned to take into account the kinetics and accumulation of PFOA, drawing on the work of Gastellu et al. 2024.

Preliminary results: Initial results show that for the daily influx of PFOA the contribution from food is much greater than from other sources. The second source is cosmetics, with about an order of magnitude difference. This is only preliminary results that must be analyzing keeping in mind that the integration of non-dietary exposure is at its early stage and needs more data. In-depth results will be obtained in the future and associated uncertainty will be discussed. This work is still in progress and a scientific publication is planned to be finalized during the last year of the project (2025-2026).

3.2.1.1.3 PFOA, Belgium – General aggregate exposure from food, air, soil, dust, and consumer products (VITO)

For the aggregate exposure modeling of PFOA in Belgium an approach similar to the French one (section above) is in progress using RSExpo. Only the input data for PFOA are described below for brevity, but similar data is available for PFOS. The aggregate exposure modeling will be conducted for both compounds.

Input data: As a reference population, the individual data from the Belgian nation **food consumption** survey BNFCS2014, which was conducted between 2014-2015 and included individuals aged 3-64 years old (Bel and De Ridder 2018) will be used. This cross-sectional study included 1000 children (3-9 years old), 1000 adolescents (10-17 years old) and 1200 adults (18-64 years old). More details on the selection of participants can be found in Bel and De Ridder 2018 and De Ridder and al. 2016. Data on food consumption, eating habits, food safety, physical activity, body weight and height amongst others were collected. Food consumption data was coded according to the FoodEx2 classification and is included in the EFSA Comprehensive European Food Consumption database. This dataset, combined with a database on PFOA concentrations in foodstuffs, allows us to estimate individual dietary exposures to PFOA for a Belgian reference population. Recently, a new sampling of foodstuffs and food contact materials (FCMs) from the Belgian market was performed in the FLUOREX study (283 food samples, 28 FCMs) (Van Leeuw et al. 2024). In the analysis 25 PFAS compounds were measured. In this study the researchers combined the food consumption data from BNFCS2014 with the concentration data to perform a dietary exposure assessment (Van Leeuw et al. 2024).

The Flemish Environmental Agency (VMM) measured **PFOA concentrations in air** in two rural background locations. Using this data (n = 112 measurements) we derive the parameters for the lognormal distribution describing this data. This is the upper bound data of TSP (Total-PFOA concentration in PM10, ng/m^3). The total PFOA concentration, i.e. linear + branched was used. One other background location, an urban location, was omitted as these data were highly elevated compared to the rural background and no lognormal distribution could be fit on the combined datasets. Data on the PUF levels (gas phase, ng/m^3) were only available for the urban background location and thus not used. The geometric mean PFOA concentration was 2.9×10^{-7} μg/m^3. The 112 measurements are directly available for use in the RSExpo model.

In Vanermen and al. 2021 some summary statistics of **PFOA soil concentrations** (μg/kg dm) in non-suspicious locations are given. The concentrations follow a lognormal distribution according to the report. The reported geometric mean ($\mu^* = 0.469$) and standard deviation ($\sigma = 0.402$) can be used to define the lognormal distribution to use in the RSExpo model.

The inclusion of exposure **through consumer products** is being developed at the moment of writing and will be included when the method is available.

Several exposure factors described in section 0 will be kept at the same value, such as the daily soil and dust ingestion, the fraction of substance in dust available for dermal contact, the amount of dust adhering to the skin, the time of home dust exposure, the fraction of the body exposed to dust and air, and daily ventilatory flow. These exposure factors do not differ per country and are kept at the same value to increase comparability between case studies.

3.2.1.1.4 PFOA, PFOS, Norway – General aggregate exposure from food, air, soil, dust, and consumer products (NIPH)

Aggregated probabilistic exposure to PFOA and PFOS from diet and cosmetic was performed in the small Norwegian study EuroMix (n=144) using custom made scripts in R (available on GitHubs). Previously, aggregated exposure to several PFAS in Norway has been performed from a duplicate diet study A-TEAM (Advanced Tools for Exposure Assessment and Biomonitoring) project using simple mathematical equations (Poothong et al. 2020b).

Input data for the different sources and routes: In the aggregated exposure to PFOA and PFOS in the EuroMix study data on food consumption from dietary records and cosmetic (personal care products) use in diaries, which were combined with information of PFOA and PFOS concentration analysis in Norwegian food and reported PFOA and PFOS concentration in cosmetics from the literature. The number of analyses varies for different food groups, where most analyses are performed of fish and sea food (n > 300) while other food groups have considerably less analyses (n = 4-65). In addition, the cosmetic specific factors such as the amount used and the retention factor for the cosmetic were taken from the literature. The number of analyses of PFOA and PFOS were much less for cosmetics than for food, and are taken from EU and Canada, making them less applicable for the Norwegian population. This adds to the uncertainty in the exposure assessment from cosmetics.

Modelling approach for aggregate exposure: A probabilistic approach was used for aggregated exposure from food and cosmetic for PFOA and PFOS. The method and results for aggregated exposure of PFOA is already published (Husøy et al. 2023), and the custom made method in R used for the probabilistic aggregated exposure are available on Github (https://github.com/TrineHusoy/PBPK_PFOA). The external exposure were modelled into an aggregated internal exposure of PFOA using a physiologically based pharmacokinetic (PBPK) model, and the model is also presented on GitHub. Similar methods were used for PFOS, and the results will be published shortly.

Results: The aggregated internal exposure to PFOA and PFOS shows that the major contribution is diet for both substances. However, PFOA is found in high concentrations in some cosmetic products, and for the participants that use these products, the contribution from cosmetics can be substantial. For seven of the participants (of 144 participants), the contribution from cosmetics were in the same range or slightly higher than from the diet. These were all females (Husøy et al. 2023) . The contribution of PFOS from cosmetics were considerably less than for PFOA, and diet was the dominating source. The methods used for probabilistic aggregated exposure in EuroMix are applicable for larger studies and can be modified for other substances than PFAS. The cosmetics exposure model in particular is selected for inclusion in the PARC model network.

3.2.1.1.5 PFOA, Netherlands – General aggregate exposure from food, and consumer products (RIVM)

Aggregated exposure to PFOA of the Dutch population was performed in **combining food and personal care products (PCPs)** exposures. This exercise served as a pilot study for coupling the PACEM Web (https://pacemweb.nl/) and MCRA (https://mcra.rivm.nl/mcra/) models with each other. The initial coupling has been performed by converting outputs from PACEM to the new input format of MCRA for externally calculated dose information. We are continuing to investigate the possibilities of a tighter coupling between PACEM and MCRA that involves fewer manual steps.

Input data for the different sources and routes: In the case study, we gathered literature data on the occurrence and concentrations of PFAS in PCPs. As there may be differences in the application of PFAS to PCPs, we chose to only use data from the EU for this stage of the case study. However, for some products only non-EU data are available, which are currently not employed. Therefore, the exposure estimated here may be an underestimation.

For PFOA, the collected EU-relevant PCP information was entered into the PACEM Web model. The results indicated that most of the Dutch population is not exposed to PFOA through PCPs. This outcome can be traced back to the occurrence fractions, which show that PFAS is relatively rarely added to PCPs in the EU. However, some of the persons that are exposed have a very high exposure, due to large PFOA concentrations measured in some products in the literature. The mean exposure of exposed persons was found to be around 0.0001 ng/kg bw/day, while the 95th percentile was found to be around 0.2 ng/kg bw/day and the 99th percentile around 0.8 ng/kg bw/day.

Modelling approach for aggregate exposure: With MCRA, the PACEM results were aggregated with the PFOA results from the Dutch Food Consumption Survey 2019-2021 (van Rossum et al. 2023)(van Rossum et al., 2023). PFOA exposure through food is common in the Netherlands. As a consequence, the aggregated PFOA exposure changes very little for most persons and for most percentiles of the population distribution, when the rare exposures through PCPs are added. However, the highest percentiles of the exposures through PCPs are much higher than the highest percentiles of the exposures through food. As a result, the very highest percentiles of the aggregate distribution are much higher than the distribution of exposures from food alone: the 99.9th percentile reported by MCRA was around 0.1 ng/kg bw/day, but becomes around 17 ng/kg bw/day, whereas the 99.99th percentile changes from around 0.2 ng/kg bw/day to around 23 ng/kg bw/day. On the other hand, the 99th percentile barely increases and stays around 0.1 ng/kg bw/day.

Results: In summary, we find in this **pilot case study that for somewhere between 0.1% and 1% of the Dutch population, PCPs are a much more significant source of PFOA exposure than food**, whereas **for the rest of the population the exposure through PCPs is negligible**. While it was known that the exposure through food is the dominant route for most of the consumer population, this study reveals that such generalizations can fail to identify very significant, even dominant, sources of exposure for subgroups of the population.

In the remaining time allotted to this case study, we intend to investigate with an updated version of PACEM Web how robust the results for these high percentiles are. We will also explore the usability of non-EU data to enhance the EU-data, especially for product categories with few or no concentration measurements from products available in the EU. Furthermore, based on this pilot study **we have described a general method for collecting and reporting data to be used on the aggregate exposure assessment of consumer products containing PFAS. This method can be applied to assess the contribution of other PFAS that are present in consumer products.**

3.2.1.1.6PFAS, Poland – Literature review on PFAS exposure sources (NIOM)

In Poland, PFAS data collection to assess the aggregate exposure was conducted primarily through organizations dealing with food safety, environmental protection and environmental monitoring. However, comprehensive and centralized databases on PFAS in different sources is not available. PFAS data in Poland is fragmented, limited and non-public. The main source of PFAS exposure information in Poland are the scientific papers, but also limited to some regions and sources.

Input data for the different sources and routes: During the review of data from institution dealing with environmental exposures such as: State Environmental Monitoring (SEM) - managed by the Chief Inspectorate for Environmental Protection (CIEP), National Institute of Public Health – National Institute of Hygiene (NIPH-NIH), National Veterinary Research Institute (NVRI), University of Agriculture in Kraków, National Veterinary Research Institute of Puławy and the EU Databases – The European Chemicals Agency (ECHA), European Food Safety Authority (EFSA) no public database on PFAS exposure in Poland was found. The only source of information was scientific reports and articles.

National Veterinary Research Institute (NVRI), University of Agriculture in Kraków, National Veterinary Research Institute of Puławy, National Institute of Public Health, University of Gdańsk are involved in studies regarding PFAS exposure in selected sources and regions with results published in scientific reports and articles.

Results: Studies conducted in Poland have demonstrated the presence of per- and polyfluoroalkyl substances (PFASs) in a variety type of foods and materials, revealing significant differences depending on the product type and source. To model the exposure from different sources it is necessary to have complete and reliable data that can cover the population whole population. In case of PFAS such data are incomplete for Poland so it does not allow for such type of estimation. Moreover, data collection occurs sporadically, primarily through targeted surveys and specific research projects, rather than as part of routine monitoring.

3.2.1.1.7PFAS, Switzerland – General aggregate exposure from food, air, soil, dust, and consumer products (Unisanté, FOPH)

The aim of this case study is to assess the aggregate exposure to PFAS in the Swiss adult population.

Input data: the case study is based on HBM data collected as part of the SHeS (Swiss Health Study) cross-sectional pilot study, which recruited a random sample of 638 individuals aged 20-69 years between 2020 and 2021. Participants were randomly selected from the population of two Swiss cantons, Vaud and Bern. Study participants completed an online questionnaire covering a range of topics including socio-demographic characteristics, medical history, lifestyle habits, quality of life and food consumption (Morand Bourqui et al. 2023). During the study visit, a series of anthropometric measurements and health tests were performed, as well as an interview on specific exposure situations. Biological samples were collected and serum samples were analysed for PFAS.
PFAS concentration data in the different sources (food, water, soil, etc.) to support the aggregate exposure modelling will be collected from the literature and supplemented by food monitoring data from Switzerland when available. For consumer products, the European database being construct can be used to provide input data.

Modelling approach for aggregate exposure: MCRA from the Parc Model Network will be used as the tool for aggregate exposure modelling.

Status of the project: The data are currently being transformed and formatted to prepare for MCRA.

3.2.1.2 Exposure to PFAS from Occupational environment to develop the worker-based approach (TNO, TTL, ENSP-UNL)

The first steps of the worker-based approach described in section 2.2.2 and Figure 6, was applied in this section to aggregate exposure from several sources related to occupational exposure. First, relevant occupations were selected based on their potential for PFAS exposure, identified through literature reviews, biomonitoring data, and datasets from the partners. This selection of occupations is based on past PFAS exposure, to ensure a sufficiency of data availability and scenario descriptions. The lessons learned on aggregation of multiple sources of PFOA and PFOS will be translated to other PFAS-related compounds to ensure the current political relevance of this work. From this data gathering effort we identified several occupations with a potential PFAS exposure, with the highest exposures occurring for chrome platers, ski waxers, fluorochemical plant workers and firefighters. Currently, we have developed and modelled exposure scenarios for chrome platers and ski waxers. The ski waxers exposure scenario is detailed in the next subsections and for chrome platers in Annex 5.1. The scenarios for the plant workers and firefighters are either still under construction or awaiting more detailed data. Exposure scenarios were developed using task-specific information such as task duration, frequency, use of personal protective equipment (PPE), environmental factors like ventilation and room dimensions, and material characteristics, including PFAS concentration and form. These scenarios were incorporated into occupational exposure models to estimate inhalation and dermal exposures. As there are no occupational exposure models available for inadvertent ingestion, we assumed a standard value from literature (if available). To refine the exposure scenarios and validate model outputs, external exposure studies with personal air or dermal measurements from similar work tasks were collected and compared to simulated ones. This work is detailed in the next subsections.

As shown in Figure 6, the next steps, will be to combine the baseline PFAS exposures from general life and environmental sources with occupational exposure estimates to calculate the total aggregate exposure. PBK modeling will be then applied to simulate internal PFAS concentrations based on the modelled data. The simulated values will be then compared with human biomonitoring (HBM) data obtained from previous studies to evaluate the accuracy and reliability of the exposure models.

3.2.1.2.1PFAS, Europe – Occupational environment, Ski waxers

Ski wax technicians frequently apply fluorinated ski waxes to skis, a process that involves heating the wax to temperatures ranging from 130–220 °C, often using ironing tools (Freberg et al. 2013; Nilsson et al. 2010a). At these temperatures, airborne particles and fumes containing various gaseous organofluorine compounds are released (Nilsson et al. 2010a). PFAS-containing products in this field predominantly include glide waxes, available in various forms such as powders, blocks, pastes, or sprays, which are applied either through heating or by abrading solid wax (Fang, Plassmann, and Cousins 2020). Traditionally, inhalation has been considered the primary exposure route for ski wax technicians. However, the common practice of allowing eating and drinking in the cabin where ski waxing takes place suggests that ingestion exposure through incidental hand-to-mouth contact may also occur (Nilsson et al. 2010b). Additionally, recent studies highlight the potential significance of dermal exposure, particularly due to the direct handling of PFAS-containing products (Freberg et al. 2010).

Exposure scenarios (Nilsson et al. 2013) conducted an observational study on PFAS exposure among ski wax technicians, which served as a primary source of information for this analysis. However, specific details regarding exposure conditions and the exact products used were limited.

During their daily tasks, ski wax technicians apply glide wax using various methods. Powdered wax is evenly sprinkled along the length of the ski sole and ironed in a single gliding motion along each side of the mid groove, often preceded by stamping to enhance adhesion. Liquid waxes are sprayed onto a cork, rubbed along the ski sole, and wiped to ensure uniform application. After wax application, technicians scrape off dried wax using plastic scrapers, polish the surface with tools like roto fleece, and finish with brushes and cleaning materials to achieve a smooth, polished state.

The cabin environment where these activities take place typically measures 30 cubic meters, with limited ventilation and no local exhaust controls during the initial stages of the study. Although gloves were used to minimize hand contact with PFAS-containing waxes, respirators were not commonly worn. During the second year of the study, local exhaust ventilation (LEV) was introduced, which may have influenced subsequent exposure measurements. Typically, only one technician was present in the cabin at a time. The PFOA content in powdered wax was reported to be higher than wax blocks and liquid formulations (Freberg et al. 2010).

Exposure modelling: PFOA exposure during ski wax application was estimated using a combination of modeling approaches. For Tier 2 evaluation, ART was applied to estimate inhalation exposure, while dART was utilized for dermal exposure. For a Tier 1 evaluation, the ECETOC-TRA v5 model was employed. To provide representative comparisons between the outputs of Tier 1 and Tier 2 models 75th percentile estimates were selected, as both tools offer this metric. A typical ski waxing work scenario involves several sequential tasks: applying wax, ironing it onto the skis, scraping off excess wax, brushing to refine the surface, and finally polishing for a smooth finish. For Tier 2 inhalation exposure modeling, these four tasks involving powdered wax were modelled in a combined scenario (Table 6).

The combined scenario included 90 minutes of sprinkling glide wax in powder form, 90 minutes of ironing powder or block glide wax, 200 minutes of scraping and brushing gliders, and 40 minutes of polishing. The scenario parameters included a workspace with a volume of 30 m^3, with no use of respiratory protection, no additional exposure sources such as co-workers, and no local exhaust ventilation. Other ART estimations were based on several assumptions. The PFOA content in ski wax powder was assumed to be 20% (217,758 ng/g) in powdered ski wax, based on reported values from older high-fluorinated formulations (Fang et al. 2020). This assumption reflects the upper range of PFOA content (3175–217,758 ng/g) and represents a worst-case scenario for occupational exposure assessment. Waxing powders were assumed to be applied with a drop height of less than 0.5 meters at rates of 10–100 grams per minute, while hot ironing involved spreading wax over surfaces of 0.3–1.0 square meters per hour. The ART model is not specifically designed to account for activities such as scraping, brushing, or polishing of dried ski wax. To address this, the ART model was adapted using a wood dust scenario as a proxy. Scraping and brushing of ski wax was assumed to generate limited dust. Ski waxing typically occurs at 130–220 °C, but the ART model is calibrated for processes up to 150 °C; thus, 150 °C was selected.

For tier 2 dermal exposure estimates, the dART model was applied. Although dART assumes uniform exposure across all skin surfaces, only hand contact with PFOA was considered, despite the possibility of whole-body exposure during certain tasks. A reduction factor of 0,1 was applied, assuming gloves were worn. The input parameters for dART, reflecting the combined exposure from the various tasks, were consistent with those used in the ART model (Table 6).

Table 6. (d)ART input ski wax technician combined scenario.

ART Question	**Input activity 1** Sprinkling powdered wax	**Input activity 2** Ironing of powder or block glide wax	**Input activity 3** Scraping and brushing gliders	**Input activity 4** Polishing gliders
Name	PFOA	PFOA	PFOA	PFOA
Exposure time (in minutes)	90	90	200	40
What is the product type of the substance / preparation?	Powders	Liquids	Solid objects	Solid objects
What is the measured dustiness of the material?	Fine dust			
What is the moisture content of the product?	Dry product		Dry object	Dry object
What is the weight fraction of the substance in the product?	0.2	0.2	0.2	0.2
What is the material of the solid object			Wood	Wood
What is the temperature of the liquid in the process?		Hot processes (50-150°C)		
What is the vapour pressure (in Pascal) of the substance at this process temperature?		10		
What is the viscosity of the substance / preparation?		Medium (like oil)		
Is the primary emission source located in the breathing zone of the worker (i.e. the volume of air within 1 meter in any direction of the worker's head)?	Yes	Yes	Yes	Yes
To which activity class does your activity belong?	Transfer of powders, falling of powders	Spreading of liquid products	Fracturing and abrasion of solid objects	Fracturing and abrasion of solid objects
Which of the situations below does best represent your activity?	Transferring 10-100 gram/minute	Spreading of liquids at surfaces or work pieces 0.3 - 1 m^2 / hour	Mechanical handling of wood resulting in limited amount of dust	Mechanical handling of wood resulting in limited amount of dust
Which equipment best describes the activity?[1]		Using short hand tool <0.5m (e.g. brush), excluding accessories		
Is the work performed in restricted workspaces? For example work in confined spaces, dense overhanging crop, underneath treated objects?[3]		No restricted workspaces		
For what purpose is the product applied?[1]		Application of coating		
What is the direction of application?[1]		Horizontal and downwards or downwards only		
What is the speed of the tool used?[1]		Low speed, e.g. wiping		
What is the type of handing?	Routine transfer			
What is the drop height?	< 0.5 m			
What is the level of containment of the process?	Open process		Open process	Open process
Are there any control measures in close proximity of the near-field emission source intended to minimize emissions from the source?	No localized controls	No localized controls	No localized controls	No localized controls

Is the process fully enclosed and is the integrity of that enclosure regularly monitored?	No	No	No	No
Are demonstrable and effective housekeeping practices in place?	No	No	No	No
Are general housekeeping practices in place?	Yes	Yes	Yes	Yes
Is the work performed indoors, outdoors or in a spray room or downward laminar flow booth?	Indoors	Indoors	Indoors	Indoors
What is the room size of the work area?	30 m3	30 m3	30 m3	30 m3
What is the ventilation rate of the general ventilation system in the work area?	0.3 ACH	0.3 ACH	0.3 ACH	0.3 ACH
Are secondary sources present in the workroom in addition to the source in the breathing zone of the worker?	No	No	No	No

1: dART specific questions.

The ECETOC-TRA model was used as a Tier 1 tool to estimate both inhalation and dermal exposures. For both exposure routes, the wax was assumed to be in a powdered state with a concentration of below 1%. Exposure was modeled under indoor conditions without local exhaust ventilation and no use of respiratory protective equipment (Table 7).

Table 7. ECETOC-TRA input ski wax technicians combined scenario.

ECETOC-Tra Question	**Input activity 1** Glide wax in powder form, sprinkling	**Input activity 2** Ironing of powder or block glide wax	**Input activity 3** Scraping and brushing gliders	**Input activity 4** Polishing gliders
Physical state	Solid	Liquid	Solid	Solid
Dustiness	High		Low	Low
Vapour pressure (Pa)		10 (200°C)		
Concentration (%)	5-25%[1]	5-25%[1]	5-25%[1]	5-25%[1]
Molecular Weight (g/mol)	414[2]	414[2]	414[2]	414[2]
PROC	8a	10	21	21
Type of setting	Professional	Professional	Professional	Professional
Task duration (min)	15-60	15-60	60-240	15-60
Ventilation	Indoors	Indoors	Indoors	Indoors
RPE	No RPE	No RPE	No RPE	No RPE

Since there are no exact process categories (PROCs) in ECETOC for the specific tasks involved in ski waxing—sprinkling powdered wax, ironing, brushing/scraping, and polishing the skis—these tasks were modeled using the closest matching PROCs based on the nature of the processes and their associated exposure risks. The PROCs applied to the different scenarios were: PROC 8a (transfer of chemicals from/to vessels/large containers at non dedicated facilities), PROC 10 (roller application or brushing), PROC 24 (high (mechanical) energy workup of substances in bound materials at temperatures below the melting point), and PROC 21 (low-energy manipulation of substances bound in materials) respectively. For the ironing of powder wax (PROC 10, liquid), a vapor pressure of 10 Pa was entered, as this value corresponds to a process temperature of 200°C.

Ingestion exposure was not estimated in this study due to the absence of suitable models for this exposure route. However, contact rates from existing literature were used to aggregate exposure.

Exposure measurement data: Research by Nilsson et al. 2013 provided relevant data on exposure levels in the above-described settings. The study, conducted across 10 different locations between 2007 and 2010, measured inhalable, respirable, and gaseous fractions of airborne fluorinated compounds during various applications of ski wax and wax grip products. The exposure measurements, reported as 8-hour time-weighted averages, reflect typical working conditions for ski wax technicians, who may work up to 30 hours per week in environments where PFAS-containing products are used. Two sampling methods were utilized in this study. Aerosol sampling involved gravimetric sampling to measure total, inhalable, and respirable fractions. Additionally, combined aerosol and gas-phase PFOA sampling was conducted using sorbent cartridges, with personal and area samples collected in parallel. Nilsson et al. 2013 reported gravimetric sampling results for total particulate aerosols with an arithmetic mean (AM) concentration of 0.012 mg/m^3 (personal sampling). Cartridge sampling for vapor-phase PFOA indicated an AM concentration of 0.000526 mg/m^3.

Aggregate exposure: To calculate the body intake per exposure route, specific assumptions regarding body uptake were applied. For inhalation, a 100% uptake rate was assumed to align with conservative exposure assessment practices, although prior research, such as by Gomis et al. 2016, suggests uptake ranges from 50–100% for PFOA. The ventilation rate was set at 0.8 m^3/hour, with an 8-hour workday total of 6.4 m^3, reflecting typical occupational breathing volumes. For dermal exposure, a 48% absorption rate was adopted based on data from Franko et al. 2012. Using a dermal permeability coefficient of 8.8×10^{-5} cm/h (Franko et al. 2012), cumulative absorption over an 8-hour workday was calculated at 0.000704 cm/hour.

Background dietary exposure to PFOA was set at 0.692 ng/kg body weight per day, as reported by (Vestergren et al. 2012). The average body weight of ski wax technicians was assumed to be 70 kg, based on (Nilsson et al. 2013). Aggregate exposure was calculated using formula 1.

Formula 1:

$$Occupational\ aggregate\ exposure = \frac{(E_{Inhalation} + E_{Dermal} + E_{Oral})}{Body\ weight}$$

PBK modelling (Next step): The outputs from (d)ART and ECETOC-TRA will be used as inputs for a PFOA/PFOS-specific PBPK model originally developed by Loccisano et al. 2011 and later adapted by Westerhout et al. 2024. This model will estimate internal exposures, which will be compared with serum concentration data by Nilsson et al. 2013 who reported measured median concentration of 220 µg/L in whole blood among ski wax technicians.

3.2.2 Cadmium: General and occupational environments for Aggregate Exposure

3.2.2.1 Exposure to cadmium from General environment

3.2.2.1.1 Cadmium, European database on concentrations in consumer product (ANSES, Unisanté, NIJZ)

One major gap identified regarding exposure data was the lack of organized data on the concentrations of chemicals in consumer products at both the national and European levels. To address this, we initiated a literature review to identify consumer products that may contain cadmium, collect data on the percentage of contaminated products, the concentration levels and to model the collected data with probabilistic distributions that can be used by the different partners in the cadmium case studies.

Prioritize cadmium-contaminated consumer products: The literature review enabled to identify cadmium-contaminated consumer products, and to gather in a database the quantitative contamination data, particularly for products available in European markets, but international products potentially sold in Europe were also considered. The review spans publications between 2013 and 2024 and corresponds approximately to the time limits of the pivotal surveys used in the modelling. Various national and international reports were consulted, along with scientific articles, institutional reports, and databases. Opportunistic reference collection was also conducted. Bibliographic query was done in the Scopus database and was based on PECOTS criteria (Population, Exposure, Comparator, Outcome, Timing, and Setting). 1455 references were identified, and the total is 1471 after combining with opportunistic searches. References were filtered based on the product type (consumer goods), type of measure (i.e. quantitative), substance measured (i.e. Cadmium) and their relevance to the European market.

Ultimately 145 references were eligible for data banking and therefore used for exposure calculations. A selection process based on the amount of available contamination data and exposure factors resulted in the prioritization of the following consumer products, all of which are cosmetics, except cigarettes: blush, body lotion, cleansers, eye pencil, eye shadow, foundation, lip balm, lipstick, mascara, moisturizer, sunscreen cream, toothpaste, powders, cigarettes. The database is available to T6.2.1 partners on the PARC sharepoint. This work is still in progress.

Modelling consumer products concentrations: The model selection process mentioned in section 2.4.1 was used, and PACEM (Christiaan Delmaar et al. 2024) emerged as the most relevant tool to model cadmium exposure through cosmetics for individuals aged over 17, although it has certain limitations, such as the impossibility of tracing individual contributions to consumer products. In this model, the concentration data must follow one of the following probabilistic laws: point, uniform, 0-truncated normal, log-normal, truncated log-normal, triangular, trapezoidal.

Noted that for cigarettes, because of the great heterogeneity of the concentration data available; the concentration information is sometimes in the cigarette, sometimes in the inhaled air, or in intermediate situations, extensive work was carried out to standardize the units before fitting the distributions. Therefore, for each selected consumer product, these probabilistic laws have been fitted on the collected data, and the best fit was selected, with the Root Mean Square Error (RMSE) criterion. These distributions estimate the actual variability of concentrations. Moreover, PACEM needs p_{exp}, the percentage of products with substance. It was proposed to estimate this quantity on the basis of banked concentration data, by calculating the ratio between the number of analysis with detection, and the total number of analysis.

3.2.2.1.2 Cadmium, France – General aggregate exposure from food, air, soil, dust, and consumer products including cigarettes (Anses)

Context and issues of cadmium exposure in France: Esteban study (Santé Publique France 2012) indicates that cadmium impregnations measured in French adults were higher than those measured in the previous French biomonitoring study (ENNS, 2006-2007). According to Santé Publique France, this trend was consistent with that observed in the Anses Total Diet Studies (TDS). The results of the TDS2 study of the general population and the TDSi study of children under the age of 3 showed an increase in dietary exposure to cadmium compared to the TDS1 study (Anses 2011a, 2016). Santé Publique France also found that the levels of cadmium measured in the urine of adults and children in France were higher than those found in most other countries (Europe and North America). Exceedances of the health guide value for cadmium recommended by Anses (Anses 2019) were observed in the Esteban study population. In fact, almost half of the French adult population exceeded the critical urinary cadmium concentration of 0.5 $\mu g.g^{-1}$ of creatinine established by Anses on the basis of bone effects. The TDSs (TDS2 and TDSi) have highlighted the overexposure of the general French population to cadmium through their diet (Anses 2011a, 2016). A health risk for consumers has not been ruled out. The main contributors to cadmium exposure among French consumers are cereals and cereal-based products, vegetables, potatoes and related products, as well as molluscs (high consumers). The implementation or reinforcement of regulatory measures to reduce human exposure to cadmium is encouraged, with the Anses proposing action on agricultural inputs to reduce cadmium contamination of soil and food (Anses 2011b), a recommendation corroborated by Santé Publique France.

Agricultural inputs through the spreading of fertilisers, livestock effluents or sludge, as well as atmospheric deposition, are sources of cadmium inputs to agricultural soils. Phosphate mineral fertilisers have been identified as a major source of cadmium in French agricultural soils (Anses 2019). In 2019, following a review of the toxicological characteristics of cadmium, Anses recommended cadmium limits in fertilisers in order to control soil contamination and agricultural production with a view to reducing consumer exposure. This recommendation is based on the construction of a 'source-to-dose' model to assess the impact on consumer health risk and to derive limit values at source to limit consumer overexposure to cadmium (Carne et al. 2021). The recommendation of cadmium limit values in fertilisers is at the interface of a regulatory context in which cadmium thresholds are now set in European regulations relating to the marketing of CE-marked fertilisers, which come into force in July 2022.

In France, a draft decree on a common safety base for fertilisers is currently being drawn up. In 2021, a case study conducted as part of "The European Human Biomonitoring Initiative" (HBM4EU) has been designed to characterize exposure using existing human and environmental biomonitoring data, with a focus on assessing the proportion of exposure from soil-contaminated food sources, based on models developed by Anses (Anses 2019). The work of the HBM4EU project highlights the fact that there has been no obvious reduction in soil cadmium concentrations and human exposure to cadmium in Europe in recent years, despite the tightening of regulations. Preliminary results confirm that there could be a significant contribution from exposure to cadmium through local food. These results only partially answer the question of whether there is a link between cadmium contamination of soils and human exposure.

In recent years, Anses has investigated several requests for proposals for maximum cadmium levels in foodstuffs, particularly in seaweed and whelks (Anses 2020a, 2020b). The exercise demonstrated the difficulty of identifying a health threshold for this contaminant, for which TDSs and impregnation studies have concluded that there is a health concern.

Faced with a situation of high dietary exposure and high cadmium impregnation of the French population, it is essential to reassess cadmium exposure from different sources and routes of exposure. The aim of this reassessment is to identify the priority levers for action to be implemented by managers, in order to reduce impregnation (Figure 26). Should action be taken on a particular food source or the last one to arrive (e.g. seaweed, whelks), on environmental sources (e.g. fertilisers, soil) or any other source (e.g. smoking)? This work is performed in collaboration with an ANSES working group of experts on this topic.

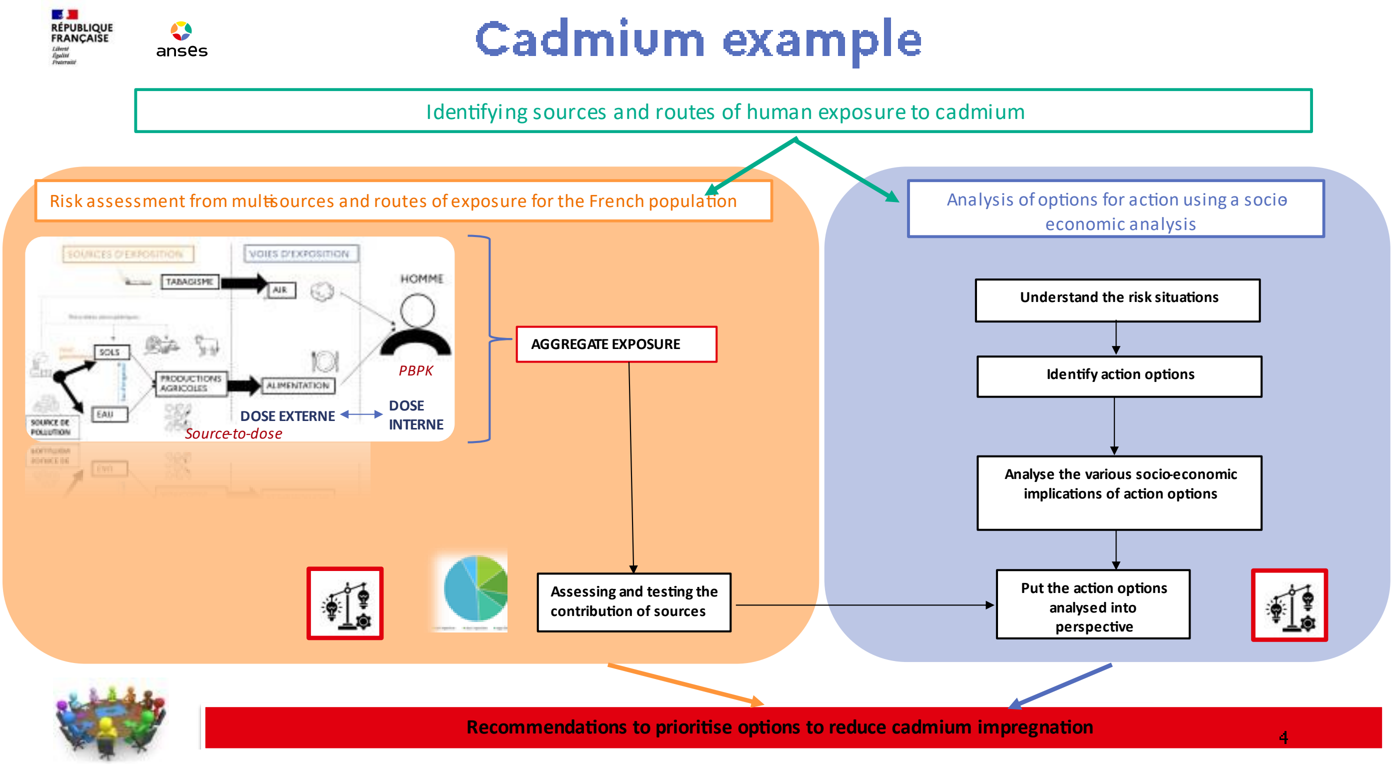


Figure 26. Aggregation of sources and routes of exposure to identify action options to reduce Cadmium impregnations in FRANCE.

Input data for the different sources and routes: A review of the sources and exposure data (exposures factors and concentration in sources) was carried out to collect the relevant exposure data to perform aggregate exposure to cadmium in France (Table 8).

Table 8. Summary of input variables used for the calculation of aggregate exposure to cadmium for French population.

Source	Routes	Exposure factors and concentration in sources	Stratification variables	References
All.	All.	Body weight (kg).	Sex, Age, Location (French administrative regions), Environment of living (rural or urban), Smoking status.	INCA2; Bebe SFAE 2005.
Diet	Ingestion.	Average daily amount of food item f, $f \in [\![1, F]\!]$, consumed by an individual (g.d^{-1}). F total number of food item.	Sex, Age, Location, Environment of living, Smoking status.	INCA2; Bebe SFAE 2005.
Diet	Ingestion.	Cadmium concentration in food (µg.g^{-1}).	Location (French administrative regions).	TDS 2, TDS infantile.
Soil	Ingestion.	Average daily amount of soil ingested by an individual (g. d^{-1}).	Age.	USEPA, 2011, EFH; USEPA, 2017, EFH.
Soil	Ingestion.	Cadmium concentration in soil (µg.g^{-1}).	Location, Environment of living.	RMQS, 2000-2009. BDSolU, 2023-2024.
Dust	Ingestion.	Average daily amount of dust ingested by an individual (g.d^{-1})	Age.	USEPA, 2011, EFH; USEPA, 2017, EFH.
Dust	Ingestion, Dermal.	Cadmium concentration in dust (µg.g^{-1}).		CSTB, 2012-2017, CNE1 school data, France.
Dust	Dermal.	Fraction of cadmium in dust available for dermal contact (/1).		Bekö, G., et al., 2013, from Vanecker, M., et al., 2020b.
Dust	Dermal.	Amount of dust adhering to the skin (g.m^{-2}).		Bekö, G., et al., 2013, from Vanacker, M., et al., 2020b.
Dust	Dermal.	Time of home dust exposure (h).		Hermant et al., 2017., from Vanacker, M., et al., 2020b.
Dust, Indoor air, outdoor air.	Dermal.	Body surface (m^{-2}).	Sex and age.	USEPA, 2011, EFH.
Dust.	Dermal.	Fraction of the body surface exposed to dust (/1).	Sex.	U.S. EPA, 2011a., from Vanecker, M., et al., 2020b.
Indoor air, outdoor air.	Dermal.	Cadmium concentration in indoor air (µg.m^{-3}).	Location.	No data in France. Hypothesis: same value as outdoor air.
Indoor air, outdoor air.	Dermal.	Cadmium concentration in outdoor air (µg.m^{-3}).	Location.	Geod'Air, 2015, PM10.
Indoor air, outdoor air.	Dermal.	Fraction of the body surface exposed to air (/1).	Sex.	U.S. EPA, 2011a., from Vanecker, M., et al., 2020b.
Indoor air, outdoor air.	Dermal.	Deposition velocity of airborne particles onto the skin's surface (m.h^{-1}).		Hermant et al., 2017., from Vanecker, M., et al., 2020b.
Indoor air, outdoor air.	Dermal, inhalation.	Fraction of daily time spent indoors (/1).	Age.	USEPA, 2011, EFH.
Air.	Inhalation.	Daily ventilatory flow (m^{3}.d^{-1}).	Sex and age.	INCA 2, from Vanacker, M., et al. 2019 ; and Vanacker, M., et al., 2020.
Air.	Inhalation.	Cadmium concentration in inhaled air (µg. m^{-3}).		Literature review (section 3.2.2.1.1).
Cigarette.	Inhalation.	Volume of one puff (m^{-3}).	Smoker or not.	Anses, UETPC.
Cigarette.	Inhalation.	Number of puffs per cigarette (dimensionless).	Smoker or not.	Anses, UETPC.
Cigarette.	Inhalation.	Number of cigarettes smoked per day (d^{-1}).	Smoker or not.	INCA 2.
Cigarette.	Inhalation.	Cadmium transfer coefficient from inhaled air to air inside lung alveola (no unit).	Smoker or not.	Satarug, S., et al., 2004.
Cigarette.	Inhalation.	Cadmium transfer coefficient from cigarette to inhaled air (no unit).	Smoker or not.	Caruso et al. 2014; Elinder et al. 1983; Fatima et al. 2019; Rubio Armendáriz et al. 2015

Cigarette.	Inhalation.	Number of smoking days per year (d.y^{-1}).	Smoker or not.	INCA 2.
Cigarette.	Inhalation.	Number of years with smoking events (y).	Smoker or not.	INCA 2.
Cigarette.	Inhalation.	Number of days in the years with smoking events, d_{exp} (d).	Smoker or not.	Elicitation.
Cosmetics.	Cosmetics - dependent	Use frequency (d^{-1})	Age, sex.	PACEM data and Ficheux, et Roudot, 2016.
Cosmetics.	Cosmetics - dependent	Use amount (g)	Sex and age.	PACEM data and Ficheux, et Roudot, 2016.
Cosmetics.	Cosmetics - dependent	Percentage of products with substance (%)	Sex and age.	Literature review (section 3.2.2.1.1).
Cosmetics.	Cosmetics - dependent	Exposure fraction (dimensionless)	Sex and age.	PACEM data and Ficheux, et Roudot, 2016.
Cosmetics.	Cosmetics - dependent	Cadmium concentration in a cosmetics(μg.g^{-1})	Sex and age.	Literature review (section 3.2.2.1.1).

Modelling approach of the retained exposure sources and routes for Cadmium: In relation to available data described in Table 8, the following exposure source-exposure route pairs were selected: Food-ingestion, Indoor settled dust-ingestion, Indoor settled dust-dermal contact, Soil-dermal contact, Air-dermal contact, Air-inhalation, Smoking, and cosmetics-dermal contact (for consumer products, section 3.2.2.1.1). Several equations published in Vanacker, Quindroit, et al. (2020b) and Vanacker, Tressou, et al. (2020) were used to modelize the different sources and routes and calculations were performed through the selected models in section 2.3: PACEM for cosmetics, RSExpo for other non-diet exposures. For food, the French exposure from two total diet studies were used.A specific modelling was applied for exposure via smoking activity using an equation based on that of Xie et al. 2012.

Simulation of internal concentrations in urine: Initially, average daily cadmium flows were calculated using absorption factors to produce internal exposures. The PBK model develop in T6.2.2 for metals (Gastellu et al. 2024) is being applied to refine results on internal concentrations. Then, simulated concentrations will be compared to French HBM survey Esteban.

Preliminary results: Initial results show that for the daily influx of cadmium the contribution from food is much greater than from other sources, and is shared for smokers with smoking exposure. In children, dust ingestion comes second. In-depth results will be obtained in the future. This is only preliminary results that must be analyzing keeping in mind that the integration of non-dietary exposure is at its early stage and needs more data. In-depth results will be obtained in the future and associated uncertainty will be discussed. A scientific publication is planned to be submitted during last year of the project 2025-2026.

3.2.2.1.3Cadmium, Belgium – General aggregate exposure from food, air, soil, dust, and consumer products including cigarettes (VITO)

For the aggregate exposure modeling of cadmium in Belgium an approach similar to the French one is in progress, using RSExpo.

Input data: As a reference population we will use individual data from the Belgian national **food consumption** survey BNFCS2014, which was conducted between 2014-2015 and included individuals aged 3-64 years old Bel and De Ridder 2018. This cross-sectional study included 1000 children (3-9 years old), 1000 adolescents (10-17 years old) and 1200 adults (18-64 years old). More details on the selection of participants can be found in Bel and De Ridder 2018 and De Ridder and al. 2016. Data on food consumption, eating habits, food safety, physical activity, body weight and height amongst others were collected. Food consumption data was coded according to the FoodEx2 classification and is included in the EFSA Comprehensive European Food Consumption database. This dataset, combined with a database on cadmium concentrations in foodstuffs, allows us to estimate individual dietary exposures to cadmium for a Belgian reference population. Both datasets are available through MCRA (de Boer and al. 2024; van der Voet et al. 2015).

The Flemish Environmental Agency (VMM) measured **cadmium concentrations in air** in two background locations, one rural background location (Koksijde) and one urban background location (Borgerhout). Both average cadmium levels in PM10 were 1×10^{-4} µg/m^3 in 2023 (PIH and al. 2024).

In 2006, the cadmium level **of 45 topsoil** (0-20 cm) samples were measured. These were all taken at non-suspect locations, and the individual measurement data are available (Seuntjens and al. 2006).

The inclusion of exposure **through consumer products** is being developed at the moment of writing and will be included when the method is available.

Several exposure factors described in section 3.2.2 will be kept at the same value, such as the daily soil and dust ingestion, the fraction of substance in dust available for dermal contact, the amount of dust adhering to the skin, the time of home dust exposure, the fraction of the body exposed to dust and air, and daily ventilatory flow. These exposure factors do not differ per country and are kept at the same value to increase comparability between case studies.

Comparison with HBM data: Direct comparison with biomonitoring data is not possible as in the BNFCS2014 no human biomonitoring was performed, but through the Flemish Environment and Health Study (FLEHS) data we have information on the cadmium levels in urine and blood of the general population. For adolescents (14-15 years old) summary data of the FLEHS IV campaign (2017-2018) on urinary (n = 415) and blood (n = 419) cadmium levels are available in Schoeters et al. 2022. For adults (50-65 years old) summary data of the FLEHS III campaign (2012-2015) on urinary (n = 207) cadmium levels are available in Schoeters et al. 2017.

3.2.2.1.4 Cadmium, Switzerland – General aggregate exposure from food, air, soil, dust, and consumer products (Unisanté, FOPH)

Input data: The Swiss Health Study - pilot phase (SHeS-pilot) (Bourqui et al. 2023; OFSP 2023) is a cross-sectional study including 789 participants from the general adult population of the cantons of Vaud and Bern of both sexes. SHeS-pilot participants answered questionnaires about their work, health, and lifestyles. They received a health check-up and donated biological samples (urine and blood). Some pollutants were measured in the participants' blood, including Cd and total Cr (Figure 27).

Available data include sex, age, residence area, smoking habits, professions, occupational exposure to fumes and dust, diet, supplementation, use of personal care products, and blood biomonitoring data on Cd and total Cr.

An analysis of this data, providing an overview of Cd and total Cr exposures among the Swiss population, considering participants' age, sex, smoking status, diet, iron and zinc supplementation, area of residence and occupational exposure, was performed and was subject of a scientific paper (Chettou et al., in preparation).

Data gathered from participants' responses to the questionnaires will be used to develop environmental exposure scenarios in a way that would allow exposure modelling using existing regulatory exposure models.

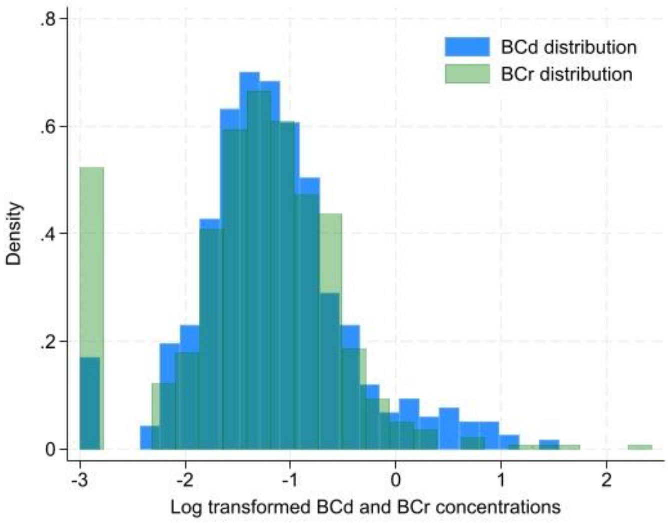


Figure 27. Distribution of BCd and BCr concentrations among the random population-based sample of the SheS-pilot study (n=638).

3.2.2.1.5Cadmium, Slovenia – General aggregate exposure (NIJZ, GeoZS, ARSO)

Interdisciplinary assessment of aggregate exposure to cadmium of adult Slovenian inhabitants.

Input data for the different sources and routes: For the case study, we selected a reference population of adults (18-64 years) from the SI-MENU 2017/18 project (food consumption), which represents the most representative sample for the Slovenian population. The survey was based on the questionnaire for the reference population (392 adults); information about age, gender, weight, region, etc. is included.

The following Cd concentration data were gathered:

Environmental exposure - individual data for house dust, topsoil and road dust, all at the same locations for the whole of Slovenia from 2016 (Teran 2020; Teran, Žibret, and Fanetti 2020). The results were obtained using different analytical methods (aqua regia and multi-acid digestion).

The individual data for PM10 particles (annual or multi-year average values) were obtained. For measuring points where metal levels in particles are monitored continuously, the average for the last five years is calculated. For other measuring points, the annual average is given, for an individual year or for several years, if measurements were carried out over several years.

Dietary exposure - cadmium concentrations in individual food samples (around 5600) from Slovenian official control 2011-2023. Missing data will be replaced with data from the literature. The results of cadmium content in individual drinking water samples (tap water) were obtained from Slovenian drinking water monitoring in the period 2013-2023 (around 4300 samples). We obtained cadmium concentrations in simulants after migration testing of food contact material from Slovenian official control (2017-2023). All chemical analysis was performed in the accredited laboratory.

Modelling approach of the retained exposure sources and routes for Cadmium: The simulations of the data will be performed in RSExpo (Environmental exposure: GeoZS and ARSO) and MCRA (dietary exposure: NIIJZ and possibly additional exposure from food contact materials: NIJZ). Simulations are planned to be performed for the whole of Slovenia, considering the meaningfulness and quality of the data also for rural/urban areas and by regions. We will exclude polluted areas (e.g. Mežica Valley, etc.).

Status of dietary exposure assessment: So far, FoodEx2 codes have been assigned and harmonized to individual foods or their groups, at the most detailed possible level of the FoodEx classification, both on the Cd concentrations in food samples and on the consumption data. This is followed by the assignment of missing data on cadmium concentrations in foods not covered by official control, preparation of final Excel tables for MCRA and simulation in

MCRA. In collaboration with J. Kruisselbrink from WUR, we will try to use MCRA to estimate cadmium exposure from food contact materials, using migration data and food consumption data in Slovenia (SI-MENU).

Comparison with HBM data and next steps: We planned to validate the estimated exposures with data from the Slovenian national HBM1 (Human biomonitoring 1) (18-49 years).

3.2.2.1.6Cadmium, Spain – General aggregate exposure (IDAEA-CSIC)

The study of cadmium exposure in the INMA cohort has involved 1346 pregnant women who provided urine in the first and the third trimester of pregnancy, 4-5-year-old 713 children and 1003 pairs of pregnant women and 9-year-old children. A subset of these 4-5-year-old children were living in a heavy industrial area.

A significant correlation of Cd concentrations in the first and third trimester of pregnancy was found ($p < 0.001$) (Fort et al. 2014). The concentrations were higher in the first than in the third trimester (Fort et al. 2014; Lozano et al. 2022).

Smoking mothers had higher Cd than non-smokers (Lozano et al. 2022). However, 4-5-year-old children from homes of smoking families did not show higher Cd urine concentrations (Junqué et al. 2022).

Mothers with higher potato consumption showed higher Cd concentrations which is consistent with EFSA 2009 reports (Lozano et al. 2022). Higher consumption of fish, eggs and oil was related with higher Cd concentrations in 4-5-year-old children (Junqué et al. 2022; Notario-Barandiaran et al. 2023). The association with oil was attributed to contaminations during oil processing and refining (Notario-Barandiaran et al. 2023)

Correlations between Cd, Pb and Ni concentrations in urine had been observed (Lozano et al. 2022).

Significant associations between higher Cd concentrations in 4-5-year-old children and reduced standing height and arm and waist circumferences were observed (García-Villarino et al. 2022).

Significant associations between higher maternal concentrations at pregnancy and 6.1% increase in behavioral problems such as inattention, hyperactivity, emotion dysregulation, aggressive/oppositional behavior in 9-year-old children has been observed (Lozano et al. 2022).

3.2.2.1.7Cadmium, Portugal ‑ General aggregate exposure (INSA)

Data on cadmium (Cd) exposure in Portugal were obtained from two main sources: i) Human biomonitoring (HBM) data from the EXPOQUIM study—Portugal's HBM4EU-aligned study on adults; and ii) Cd occurrence levels in food, as reported by Portugal to EFSA.

The EXPOQUIM study was a cross-sectional survey involving adults aged 28 to 39 years old who had been living in Portugal for more than three years. First-morning urine samples were collected for the analysis of selected chemicals, including Cd. Sample collection took place across mainland Portugal and the islands of Madeira and the Azores between May 2019 and March 2020. Participants also completed Food Frequency Questionnaires (FFQs), providing data on the frequency of consumption of various food groups, including fish, meat, vegetables, fruits, dairy products, eggs, bread and cereal-based products, snacks, as well as smoked, grilled, and ready-to-eat foods. Additional data for the same participants on the frequency of use of cosmetic products and tobacco consumption were also collected.

Cd food occurrence data were derived from the national transmission of food monitoring data to EFSA, covering reported occurrence levels in various food products from 2009 to 2023.

Additionally, national dietary consumption data for Portugal are available through the National Food, Nutrition and Physical Activity Survey (IAN-AF). This survey used a multistage sampling approach based on the National Health Registry to ensure a representative sample of the Portuguese population, covering individuals from three months to 84 years of age. The final survey included 5 811 participants, each providing two dietary assessments (Lopes et al. 2017). Data was collected during 12 months (October 2015 to September 2016), distributed over the four seasons and including all days of the week, in order to incorporate seasonal effects and day-to-day variation in food intake and physical activity.

3.2.2.2 Exposure to cadmium from Occupational environment to develop the worker-based approach (TTL, TNO, UNISANTE, ENSP-UNL, STAMI, IVL, LNS, ANSES, INRS)

Similarly as to PFAS, the first steps of the worker-based approach as described in section 162.2.2 and Figure 6, were applied in this section to estimate the aggregate exposure originating from several occupational sources. First, relevant occupations were selected based on their potential for Cadmium exposure, identified through collected data sets from partners including biomonitoring data, and exposure assessments (Table 9). From this available data, we identified the following occupations that can lead to Cadmium exposure: ash removal workers in power plant boiler (inhalation exposure), maintenance workers in power plant boiler (inhalation exposure), Silver-Cadmium solderers (hard soldering), manual glass manufacturers preparing red colored batch, melting of batch, and blowing or pressing of glass products, electronic waste workers exposed to cadmium in batteries recycling. In addition, literature review is ongoing to identify other possible occupations exposed to cadmium. For these identified occupations, seven different exposure scenarios have been developed based on the available research data. In Table 4 is presented the summary of the progress of each case study.

First exposure scenarios were developed using task-specific information such as task duration, frequency, use of personal protective equipment (PPE), environmental factors like ventilation and room dimensions, and material characteristics, including cadmium concentration and form. These scenarios were incorporated into occupational exposure models to estimate inhalation, dermal, and oral exposures. Model selection for each exposure scenario was conducted following the modelling step by two experienced modelers. To refine the exposure scenarios and validate model outputs, external exposure studies with personal air measurements from similar work tasks were collected and compared to simulated ones. After the comparison of the modelling results of the two modelers, exposure scenarios were further developed to be more detailed if needed to receive more precise and uniform modelling results. Currently, an excel table for the results is formed to collect results of modeled external exposure results and data of measured external exposure in a harmonized and comparable way. Different exposure models produce results in distinct manners, creating a challenge for data comparison, thus, a harmonized way to present the result of modeling is required. Then, comparison of modelled external exposure results of the case studies is compared to measured external exposure levels. Next step is to perform PBK modelling to produce internal exposure levels using the one implemented in the PARC model network (MCRA). More detailed information on the ash removal exposure scenario in power plant boilers, using inhalation exposure as an example, is provided below. Detailed information of other exposure scenarios can be found in Annex 5.2.

Table 9. Datasets used in the assessment of aggregated occupational exposure of cadmium.

Country/research	Database	Substances	Data included	Years covered	Where can be used
Finland	Biomonitoring registry database	Cd, Cr, others	occupation, industry sector, BM results	2010-2022 (also older data available)	Comparison and validation with simulated internal exposure data
Finland	Air monitoring registry database	Cd, Cr, others	industry sector, air sampling results	2010-2022 (also older data available)	Comparison and validation with simulated external exposure data
HBM4EU	Research data from occupational studies (welding, Chrome platers and e-waste workers)	Cd, Cr, PFAS, Phthalates	contextual data for modelling of exposure, and measured inhalation, dermal and biomonitoring data	2017-2022	Building exposure scenarios
Finland	Research data from	Cd	contextual data for modelling of exposure,	2005-2008	Building exposure scenarios

	occupational studies (glass industry workers)		and measured inhalation, and biomonitoring data		
Finland	Research data from occupational studies (power plant workers)	Cd	contextual data for modelling of exposure, and measured inhalation, dermal and biomonitoring data	2010-2011	Building exposure scenarios
France	INRS air monitoring database	Cd, Cr, plasticizers.	aggregated concentration data, with contextual information.	1987-2024	Comparison and validation with simulated chemical air concentrations in the occupational setting.
France	Air monitoring data among French battery recyclers	Cd, Cr	Concentration in airborne samples, taking into account the assigned protection factors for respiratory masks.	2018-2019	Comparison and validation with simulated chemical air concentrations in the occupational setting.
Norway	Biomonitoring registry database	Cd, Cr	Aggregated data	1984-2016 1984-2013	Comparison and validation with simulated internal exposure data
Norway	Air monitoring registry database	Cd Cr	Aggregated data for Cd available now. ISCO-08 coding for Cr under work	1982-2024	Comparison and validation with simulated internal exposure data
Switzerland	Swiss Health Study (SHeS-pilot)	Cd, Cr	sex, age, residence area, smoking habits, occupational exposure to fumes and dust, diet, supplementation, use of personal care products, and Cd and total Cr blood biomonitoring data.	2020-2021	Building exposure scenarios Comparison and validation with simulated internal exposure data
Switzerland	Swiss National Accident Insurance Fund (SUVA) database	Cd, Cr	Sex, age range, activity sector, workplace description, and Cd and Cr urinary biomonitoring data.	1989-2024	Building exposure scenarios Comparison and validation with simulated internal exposure data

3.2.2.2.1Cadmium, Europe – Occupational environment, Ash removal in power plant boiler– inhalation exposure

Finnish research data (2010-2011) was used to develop exposure scenarios from the exposure to Cd in ash at power plant. Exposure is modeled based on two exposure scenarios: ash removal in power plant boiler and maintenance work in power plant boiler. Here, exposure scenario of the Ash removal in power plant is described in the Table 10 and Table 11 and the exposure scenario of the maintenance work is described in the Annex 5.2.1. First, a general description of exposure situation (Table 10) is described including detailed information about exposing substances and its character. Secondly, the exposure scenario (Table 10) is described including description of the activities during the work task, working time, ventilation, personal protective equipment, and other working conditions. Based on this information modelers could build a modelling of the exposure scenario.

Exposure scenario for ash removal: Table 10 and Table 11 present the general description of exposure situation as well as the exposure scenario and their determinants.

Table 10. General description of exposure situation.

Product/ exposing material	Supplier	Substance name	CAS number	Molecular weight (g/mol)	Physical state	Vapor pressure in 20°C/Pa	Dustiness (coarse, medium, fine)	Concentration of the substance in product or exposing material (%)
Ash at biomass-fired power plant	-	Cadmium	7440-43-9	112,41	solid	-	fine	Peat < 0,00015 Wood pellets < 0,0015 Wood < 0,0030 REF < 0,0045

Table 11. Exposure scenario of ash removal in power plant boiler.

Ash removal in power plant boiler	
Description of activities	The operator removes burned material and bottom and fly ash using shovel and vacuuming
General ventilation (ventilation rate if available)	Keep the bottom hatches of boiler open to create ventilation inside the boiler
Local ventilation (ventilation rate if available)	None
Respiratory protective equipment	Powered air respirator with ABEK+P3 cartridges
Work clothing and use of protective gloves	Hooded one-piece coveralls, over-wrist long leather gloves
Room temperature	20-40 C
Room size (small, medium, large, dimensions if available m^3)	small
Time (hours) used for the activity per day	8-12
Other relevant parameters	Power plant must shut down two days before ash removal workers enters inside power plant boilers. Concentration of gases must be measured before entering inside the power plant boiler. Ash removal worker should use carbon monoxide gas monitor during working inside power plant boiler. Large ash accumulations may be still hot when ash removal starts, and they can cause skin burns, evaporate gases, or melt down ash removal hoses. Worker should wash their hands before eating drinking or smoking, and these activities are prohibited inside the boiler. Exposure assessment of worker to Cd (if needed): The urine biomonitoring samples, immediately after workday.

Model selection and results: External exposure model selection has been made according to steps of the model selection-description algorithm and suitable model for inhalation exposure is ART. Modelling has been conducted by two experienced modelers. There were modeler specific differences in the results. To reduce variation between the modelers, modelers have been working the scenario description to be more specific. Parts causing the variation in the results were identified by comparing the modeling reports. Following more detailed exposure scenario description new modellings will be made and results will be compared with measured data.

3.2.2.3 Exposure to cadmium from Occupational environment to develop the population-based approach (TTL, TNO, ANSES, UNISANTE)

The first steps of the population-based approach as described in section 2.2.2 and Figure 6, was applied in this section. The prevalence of different occupations were gathered from various national or international population based surveys (e.g. Eurostat Labour Force survey). JEMs are required to estimate the exposure levels at the population level, for which a literature search was performed as well as a check in the EU JEM inventory tool (https://occupationalexposuretools.net/). For comparison purposes various details on the JEMs have been collected, such as the year of coverage, and the classification level used. The existing JEMs will be updated with the estimates from the worker-based approach where possible. As shown in Figure 6, the next steps will be to combine the (updated) JEMs with the prevalence of occupations, resulting in the proportion of the working population exposed. This information can be compared to the results of the project P4.1.1.4a Feasibility study for Cadmium.

JEMS review results: There are JEMs available for Cd exposure Table 13. Most of the available European JEMs for Cd are based on the Finnish JEM (FINJEM) (* in table above). However, when FINJEM has been used as a basis, reassessment of some estimates may have been done. JEMs, together with information on the prevalence of different occupations in the given population can be used to estimate the contribution of occupational exposure to general population U-Cr and U-Cd levels. These estimates can be compared to the available general population HBM data. In the case of Cd and Cr occupational exposures in general population HBM datasets have been analyzed in P4.1.1.4.a, which results have been reported in AD4.8. Further comparisons on the proportion of the specific occupational groups in the HBM datasets and Eurostats information on occupations are made as part of this task. Overall progress in the population-based approach is presented in Table 12**Erreur ! Source du renvoi introuvable.**.

Table 12. Progress on the population-based approach for Cadmium and Chromium.

Country	Case	Prevalence of occupational groups	JEMS	Proportion of working population exposed	Exposure levels	PBPK modelling	Comparison to general population data	RA/HIA
Finland	Cd	X	X	X	X			
France	Cd	X	Not available					

IP= In progress, RA= Risk assessment, HIA= Health impact assessment

For example, in FINJEM the exposure is assessed if at least 5% of the workers in each occupation have been exposed to an annual mean level of 0.5 ug/m^3 of Cr or Cd at any time in 1945-95. It is advised to use the occupational classification of the JEM, while converting the JEM occupational coding to another is laborious and may cause discrepancy in JEM estimates. In case of Cd, the number of exposed workers is nowadays limited, which limits the possibilities to identify these occupationally exposed worker groups in general population HBM datasets, as noted in AD4.8 (PARC-T4.1 group 2024).

Table 13. Available JEMs for cadmium.

JEM (and region)	Cd	Time-resolved	Classification	Contact person
FINJEM (Finland)	x^3	1945-2015	ISCO-58 based FINJEM coding	Sanni Uuksulainen (sanni.uuksulainen@ttl.fi)

FISCO88 FINJEM 2019 (Finland)*	x[3]	1995-2009	ISCO-88 based FISCO-88	Sanni Uuksulainen (sanni.uuksulainen@ttl.fi)
SWEJEM (Sweden)*	x[3]	1960-2015	ISCO-88 based SSYK96 for Cr ISCO-58 based FoB80 for Cd	Jenny Selander (jenny.selander@ki.se Pernilla Wiebert (pernilla.wiebert@ki.se)
MatEmEsp (Spain)*	x[3]	1996–2005	ISCO-88 based Spanish CNO94	Ana M Garcia (Ana.M.Garcia@uv.es) Michelle Turner (michelle.turner@isglobal.org)
INTERROC JEM*	x[3]	1945-2006	ISCO-68	Martie van Tongeren (martie.j.van-tongeren@manchester.ac.uk)
SIMEX-JEM (France)	x	-	French classification PCS 1994	Marcel Goldberg (marcel.goldberg@inserm.fr)

[3] Includes metallic cadmium and all cadmium compounds

* based on FINJEM

Usability of FINJEM for cadmium: Altogether 17 occupational groups are exposed to cadmium according to FINJEM (FINJEM Excel 2016c), which uses FINJEM occupation classification (close to ISCO58). Occupational group may consist of several subgroups with different tasks and not all employers in the group are regarded as exposed. The prevalence of exposed shows the amount exposed in the occupation group. In cadmium exposed occupations, the FINJEM prevalence varies from 0.1% to 10%, which means that in the most exposed occupational group, no more than one in ten is exposed.

Among these 17 occupational groups, there are altogether about 900 cadmium exposed workers in Finland (years 2013-15). Since the average number of workers/year in Finland during that period was about 2447000, only about 0.04% of the population was exposed to cadmium. If a sample of one thousand people is biomonitored, there might be only a maximum of 1 person representing these Cd exposed groups. It should be noted that the present FINJEM should be updated by ignoring the occupations where prevalence is less than 5%, which is the original threshold limit. If we use this 5% threshold, there will be only 6 exposed occupational groups in 2023-15 and the amount of exposed in the population is about 0.01% (Table 14). Assuming that the prevalence is similar also in other countries, this explains why these occupational groups were not came up in the analysis of general population HBM data made under P4.1.1.4b even though the population was >2000 adults (AD4.8) or in the analysis made in France from ESTEBAN cohort (Santé Publique France 2012).

Table 14. Cadmium exposed occupational groups and their prevalence of exposure and number of exposed in FINJEM.

ocode	Label in English	Prevalence of exposure [%]	Level of Exposure [ug/m^3]	Number of workers	Number of exposed
731	Cookers and furnacemen (chemical processes)	10	3,8	482	48
630	Metal smelting furnacemen	10	1,2	1051	105
714	Glass and clay mixers	10	1	3	0
713	Glass and ceramics decorators, ceramics dippers	5	2	119	6
634	Foundry Workers	5	0,5	1214	61
644	Goldsmiths, silversmiths etc.	5	0,5	1156	58
	total number of workers/exposed			4025	278
	divided by **2447000** (average number of workforce in Finland 2013-15)			0,0016449	**0,000114**

3.2.3 Chromium: General and occupational environments for Aggregate Exposure

3.2.3.1 Exposure to Chromium from General environment (FOPH, INSA, Anses, INRS, CSTB, GeoZS, NIJZ, ARSO, VITO, KWR, IVL, IDAEA-CSIC)

Work on estimating exposure to chromium in the general environment has not yet begun, and will start in 2026.

3.2.3.2

3.2.3.3 Exposure to Chromium from Occupational environment to develop the worker-based approach (TTL, TNO, UNISANTE, ENSP-UNL, STAMI, IVL, LNS, ANSES, INRS)

The first steps worker-based approach described in section 2.2.2 and Figure 6, was applied in this section to aggregate exposure from several sources related to occupational exposure. First, relevant occupations were selected based on their potential for chromium VI exposure, identified through collected data sets from partners including biomonitoring data, and exposure assessments (Table 15). From this available data, we identified the following occupations that can lead to chromium VI exposure: Chrome platers (loading with cranes/manual plating), chrome platers (Automatic), chrome platers (automatic wet grinding), Spray painters of aircrafts (full body) with paints with chrome, Spray painters of aircrafts parts with paints with chrome, welders, and steel factory workers (hot rolling mill). In addition, literature review is ongoing to identify other possible occupations exposed to chromium VI. For these identified occupations, eight different exposure scenarios have been developed based on the available research data. In Table 4**Erreur ! Source du renvoi introuvable.** is presented the summary of the progress of each case study.

Following the same strategy as the PFAS and Cd case, exposure scenarios were developed and modeled. Two experienced modelers performed the modelling, the results of which were checked for consistency. The agreed upon external modeled values are to be combined with the general environment (activity to be started in 2026). More detailed information on the steel factory workers (hot rolling mill) exposure scenario as an example, is provided below in the own sub-section. Detailed information of other exposure scenarios can be found in Annex 5.3.

Table 15. Datasets used in the assessment of aggregated occupational exposure of chromium.

Country/research	Database	Substances	Data included	Years covered	Where can be used
Finland	Biomonitoring registry database	Cd, Cr, others	occupation, industry sector, BM results	2010-2022 (also older data available)	Comparison and validation with simulated internal exposure data
Finland	Air monitoring registry database	Cd, Cr, others	industry sector, air sampling results	2010-2022 (also older data available)	Comparison and validation with simulated external exposure data
HBM4EU	Research data from occupational studies (welding, Chrome platers and e-waste workers)	Cd, Cr, PFAS, Phthalates	contextual data for modelling of exposure, and measured inhalation, dermal and biomonitoring data	2017-2022	Building exposure scenarios
Finland	Research data from occupational studies (steel factory workers)	Cr (VI)	contextual data for modelling of exposure, and measured inhalation, dermal and biomonitoring data	2021-2022	Building exposure scenarios

France	INRS air monitoring database	Cd, Cr, plasticizers.	aggregated concentration data, with contextual information.	1987-2024	Comparison and validation with simulated chemical air concentrations in the occupational setting.
France	Air monitoring data among French battery recyclers	Cd, Cr	Concentration in airborne samples, taking into account the assigned protection factors for respiratory masks.	2018-2019	Comparison and validation with simulated chemical air concentrations in the occupational setting.
Norway	Biomonitoring registry database	Cd, Cr	Aggregated data	1984-2016 1984-2013	Comparison and validation with simulated internal exposure data
Norway	Air monitoring registry database	Cd Cr	Aggregated data for Cd available now. ISCO-08 coding for Cr under work	1982-2024	Comparison and validation with simulated internal exposure data
Sweden	SafeChrome	Cr			Comparison and validation with simulated chemical air concentrations in the occupational setting.
Switzerland	Swiss Health Study (SHeS-pilot)	Cd, Cr	sex, age, residence area, smoking habits, occupational exposure to fumes and dust, diet, supplementation, use of personal care products, and Cd and total Cr blood biomonitoring data.	2020-2021	Building exposure scenarios Comparison and validation with simulated internal exposure data
Switzerland	Swiss National Accident Insurance Fund (SUVA) database	Cd, Cr	Sex, age range, activity sector, workplace description, and Cd and Cr urinary biomonitoring data.	1989-2024	Building exposure scenarios Comparison and validation with simulated internal exposure data

3.2.3.3.1 Chromium, Europe – Occupational environment, Steel factory workers, hot rolling mill

Finnish research data (2021-2022) was used to develop exposure scenarios from the exposure to Cr in steel factory workers at hot rolling mill. Exposure scenario of the steel factory workers is described in the Table 16. First, a general description of exposure situation (Table 16) is described including detailed information about exposing substances and its character. Secondly, the exposure scenario (Table 17) is described including description of the activities during the work task, working time, ventilation, personal protective equipment, and other working conditions. Based on this information, modelers build a modelling of the exposure scenario. First version of exposure scenario and model selection of hot rolling mill was prepared. Next, review of the model description is made, and more precise and detailed exposure scenario is performed.

Exposure scenario for Steel factory workers, hot rolling mill: Table 16 and Table 17 present the description of exposure situation, exposure scenario and their determinants

Table 16. General description of exposure situation.

Product/exposing material	Supplier	Substance name	CAS number	Molecular weight (g/mol)	Physical state	Vapor pressure in 20°C/Pa	Dustiness (coarse, medium, fine)	Concentration of the substance in product or exposing material (%)	Amount of product or exposing material used (kg or Liter or kg/min)
Cr(VI) in steel manufacturing, hot rolling mill	-	Hexavalent chromium	7440-47-3	51,9961	solid	Melting point 1907°C, boiling point 2671°C	coarse, medium and fine dust	Metallic Cr >10.5 % in steel, Cr(VI) 0.0025-0.044 % in inhalable dust	2280 kg/min of steel

Table 17. Exposure scenario of steel factory workers.

Steel factory workers - hot rolling mill	
Description of activities	Automated hot rolling of steel slabs (massive objects) in a factory hall. During production, the workers mainly at control rooms, but also service work carried out at the factory hall during production. During scheduled maintenance breaks, the workers are mainly performing maintenance works at the factory hall. Chromium present in metallic form in stainless steel, surface oxidation layer has Cr(III) compounds Dust particles including Cr(VI) are formed during the heating and hot rolling of stainless steel slabs (not present in the raw material or the final product)
General ventilation (ventilation rate if available)	yes
Local ventilation (ventilation rate if available)	yes, process has own integrated exhaust ventilation
Respiratory protective equipment	RPE is used in specific work tasks: EN140 (APF=20) or TH3P (ABEK+P3) (APF=40)
Work clothing and use of protective gloves	Protective clothing: Clothing to protect against heat and flame (EN ISO 11612), in dusty work tasks also: Chemical protective clothing (type 5) Protective gloves & goggles used. Type depends on the work task in question: most commonly leather work gloves (e.g., EN 388:2016+A1:2018) or incision-resistant gloves (level 5) (EN 1082-2:2000 or EN ISO 13997, at least class D). Some work tasks require also protective gloves against thermal risks (heat and/or fire) (EN 407:2004) or chemical protective gloves (EN ISO 374).
Room temperature	elevated room temperature (25-45 °C) due to high temperature process
Room size (small, medium, large, dimensions if available m^3)	large (length 150m, width 30 m, height 15 m)

Time (hours) used for the activity per day	from 5 mins to 5 hours of exposing work in the process hall, otherwise control room work
Other relevant parameters	Formation of dust to air from hot rolling milling the steel slabs (inhalation exposure potential). The process emissions are partly dispersed to the factory hall. Process machinery has own exhaust ventilation, but efficiency limited. Process temperature 1200 °C (steel slab) Dust collected on all room surfaces (dermal exposure potential). Premises and equipment are cleaned and maintained (occasionally the factory hall floor might not be cleaned resulting in a dust layer on the floor and other surfaces). Near-field and far-field exposure both possible, mostly far-field exposure. Measured exposure concentration at worker breathing zone, Cr(VI) in inhalable dust: <0.0001–0.0003 mg/m^3 (average 0.00006 mg/m^3, n=45). Concentration during maintenance breaks is 17–68 % of the concentration during production.

Model selection and results: External exposure model selection has been made according to steps of the model selection-description algorithm and a suitable model for inhalation exposure is TREXMO (MEASEv1 or EASE 2.0) or MEASEv1 excel sheet and for dermal exposure MEASEv1 (excel sheet) or MEASEv2. Modelling has been conducted by two experienced modelers. There were modeler specific differences in the results. To reduce variation between the modelers, modelers has been working the scenario description to be more specific. Following more detailed scenario description new modellings will be made.

3.2.3.4 Exposure to chromium from Occupational environment to develop the population-based approach (TTL, TNO)

For population-based approach possible JEMs have been searched. Most of the available JEMs only include estimates on the total Cr exposure, not on CrVI exposure. SYN-JEM and DOMJEM have been identified to include hexavalent chromium exposure. Access to use these JEMs for our purposes has been requested. In addition, Eurostat microdata (4 digit ISCO level) has been requested to be able to calculate prevalence of occupational groups. The calculation of the proportion of the working population exposed and exposure levels using JEMs and Eurostat is to be developed.

3.2.4 Plasticizers: General and occupational environments for Aggregate Exposure

3.2.4.1 Exposure to Plasticizers from General environment (IVL, Anses, CSTB, LNS, Unisanté, TTL)

Partners from Finland, France, Luxembourg, Sweden and Switzerland have expressed an interest in carrying out work to estimate plasticizers aggregate exposure in their general population. On the basis of health concern, regulatory interest and data abundance, the following plasticizers have been prioritized: DBP, BBP, DINP, DEHP, DIDP, DMP, DINCH, DPHP. Data organization and calculations will start in 2026.

3.2.4.2 Exposure to Plasticizers from Occupational environment to develop the worker-based approach (TTL, UNISANTE, ANSES, TNO, IVL, ENSP-UNL, WUR, IDAEA-CISC, LNS, RUMC, LNS, INSA, NIJZ, CSTB)

The first steps worker-based approach described in section 2.2.2 and Figure 5, was applied in this section to aggregate exposure from several sources related to occupational exposure. First, relevant occupations were selected based on their potential for plasticizers exposure, identified through lit collected data sets from partners including biomonitoring data, and exposure assessments (Table 18). From this available data, we identified the following occupations that can lead to plasticizers exposure: plastic carpet removers at demolition site, plastic products manufacturers, manufacturing tarpaulins by extrusion, electronic waste workers exposed to plasticizers in batteries recycling, schoolteachers, and professional printers. For these identified occupations, currently five different exposure scenarios have been developed based on the available research data. Unisanté will have new research data coming on 2025 that could be used to build an additional exposure scenario for professional printers. In addition, a literature search was conducted to find possible case studies, but no suitable data was found. In Table 9is presented the summary of the progress of each case study.

Following the same strategy as the other case studies, occupational exposure scenarios were developed and modeled. Two experienced modelers performed the modelling, the results of which were checked for consistency. The agreed upon external modelled values are the combined with the general environment (activity to be started in 2026). More detailed information on plastic carpet removal at demolition site as an example, is provided below in the own sub-section. Detailed information of other exposure scenarios can be found in Annexes 5.4.

Table 18. Datasets used in the assessment of aggregated occupational exposure of plasticizers.

Country/ research	Database	Substances	Data included	Years covered	Where can be used
Finland	Research data from occupational studies (plastic product manufactures)	Plasticisers	contextual data for modelling of exposure, and measured inhalation, and biomonitoring data	2014-2016	Building exposure scenarios
Finland	Research data from occupational studies (plastic carpet removals)	Plasticisers	contextual data for modelling of exposure, and measured inhalation, and biomonitoring data	2014-2016	Building exposure scenarios
France	Research data from occupational studies for school teachers.	Phthalates, pesticides, flame retardents, PAHs	contextual data for modelling of exposure	2013-2017	Building exposure scenarios
France	INRS air monitoring database	Cd, Cr, plasticisers.	aggregated concentration data, with contextual information.	1987-2024	Comparison and validation with simulated chemical air concentrations in the occupational setting.

3.2.4.2.1Plasticizers, Europe – Occupational environment, Plastic carpet removers

Finnish data (2014-2016) was used to develop exposure scenarios from the exposure to Plasticisers for Plastic carpet removers. Exposure scenario of the steel factory workers is described in the Table 19. First, a general description of exposure situation (Table 19) is described including detailed information about exposing substances and its character. Secondly, the exposure scenario (Table 20) is described including description of the activities during the work task, working time, ventilation, personal protective equipment, and other working conditions. Based on this information, modelers build a modelling of the exposure scenario. First version of exposure scenario and model selection of plastic carpet removers was prepared. Next, review of the model description is made, and more precise and detailed exposure scenario is performed.

Table 19. General description of exposure situation.

Product/exposing material	Supplier	Substance name	CAS number	Molecular weight (g/mol)	Physical state	Vapor pressure in 20°C/Pa	Dustiness (coarse, medium, fine)	Concentration of the substance in product or exposing material (%)
Plastic carpets to be removed, containing phthalates	-	DEHP, DBP, BBP (not known exactly, as carpets were old)	117-81-7 84-74-2 85-68-7	390,56 278,34 312.37		3.4×10^{-5} 2.67×10^{-3} *0.001*	fine	PVC carpet used in public areas typically contains max 20% w/w plasticizers (one or more)

Table 20. Exposure scenario of plastic carpet removal work at demolition site.

Plastic carpet removal work at demolition site	
Description of activities	The construction worker removes old, glued carpet from the concrete floor manually tearing or ripping, using a knife or similar hand-held tools to help with the removal.
General ventilation	May be assumed that air condition was still on while removing work
Local ventilation	None
Respiratory protective equipment	None
Work clothing and use of protective gloves	Short sleeved T-shirt, leather-textile gloves
Room temperature	Normal office temperature, 20-22 C
Room size (small, medium, large)	medium
Time (hours) used for the activity per day	Realistic case could be 4 hours tearing the carpets, but other work tasks may also include exposure to phthalate remnants (cutting and chiseling concrete structures and floor)
Other relevant parameters	near-field exposure It needs to be noticed, that it is assumed in (withdrawn) AfA documents, that only dermal exposure takes place in this task.

Model selection and results: External exposure model selection has been made according to steps of the model selection-description algorithm and a suitable model for inhalation exposure is ART and for dermal exposure ECETOC TRA. Modelling by second modeler is under progress.

3.2.4.3 Exposure to plasticizers from Occupational environment to develop the population-based approach (TTL, TNO)

For population-based approach possible JEMs have been searched. SUMEX2 and UK JEMS have been identified to include plasticizers exposure. The suitability of these JEMS for this exercise has been studied. The Sumex2 JEM can be used for population-based method, but likely only in France due to unique occupation and industry definitions that are not easily transferrable to other countries.

Access to use the UK JEM for our purposes has been requested. In addition, Eurostat microdata (4-digit ISCO level) has been requested to be able to calculate prevalence of occupational groups. The possibility to calculate the proportion of the working population exposed end exposure levels using JEMs and Eurostat will be studied.

3.2.5 Pyrethroids: General and occupational environments for Aggregate Exposure

3.2.5.1 Exposure to Pyrethroids from General environment (Anses, CSTB, BPI, ISSeP, RU, NIOM, ISCIII, Unisanté)

Partners from Belgium, France, Greece, Italy, The Netherlands, Poland, Spain and Switzerland have expressed an interest in carrying out work to estimate pyrethroids aggregate exposure in their general population. An initial list of 33 pyrethroids was built from pyrethroids in the list of the HBM4EU report (HBM4EU 2022), completed by pyrethroids studied in two EFSA reports on cumulative dietary assessment (EFSA 2019; van Klaveren et al. 2019), and confronted for possible consolidation to pyrethroids among which a use has been identified in plant protection products, or biocides, or veterinary medicines, or human medicines. Then, it was decided to use the approval status as first criteria to selected approved one from the initial list of 33 pyrethroids: the list of 30 approved pyrethroids since 2017 was used to continue with the application of other criteria. The other criteria are: Availability of biomonitoring surveys; Existence of regulatory and sanitary interest; Existence of at least one partner reported data in one source of exposures for one partner; Presence in EFSA CAG classification in connexion with the P6.2.3 Real-life mixture project; With metabolites; modeled in PBK models. The application of selection criteria conducted to a list of 14 pre-selected pyrethroids: Alpha-cypermethrin, Cypermethrin, Deltamethrin, Lambda and Gamma Cyhalothrin, Permethrin, Tetramethrin, Flubalinate (tau-), Bifenthrin, Cyfluthrin, Esfenvalerate, Tefluthrin, Cyphenothrin, Etofenprox. Data organization and calculations will start in 2026.

3.2.5.2 Exposure to Pyrethroids from Occupational environment (ISCIII, RUMC, BPI)

In the case of occupational exposure estimations from pyrethroids, the non-dietary exposure for operators/workers/bystanders/residents can be calculated based on pesticide application data and considering specific agricultural practices/possible risk mitigation measures applied. This requires monitoring of how pesticides are applied by operators and details of mitigation measures used to reduce exposure (e.g. personal protective equipment, drift reduction nozzles, buffer zones), information about hours worked, frequency of application or other working activities performed by the operator/worker that may contribute to the exposure. However, this kind of data is not routinely collected/recorded, at least not by all farmers. To address this matter, EFSA has funded specific projects in order to address this issue, i.e. EFSA PPR Procurement Projects:

“Collection and assessment of data relevant for non-dietary cumulative exposure to pesticides and proposal for conceptual approaches for non-dietary cumulative exposure assessment” (CT/EFSA/PPR/2010/04) and “Collection of pesticide application data in view of performing Environmental Risk Assessments for pesticides” (CFT/EFSA/PPR/2012/05).

The overall objective of the work was the elaboration of a data collection strategy and the initiation of data collection appropriate for the cumulative non-dietary exposure of operators and workers to multiple active substances used for crop protection but also for environmental risk assessment.

The available data will be analyzed and further considered to structure specific scenarios for conducting a retrospective aggregated non-dietary exposure assessment in the following pyrethroid case studies.

3.2.5.2.1 Pyrethroids, Europe – Occupational environment, Non dietary exposure in agricultural setting (UNIMI, ICPS, UNIPD)

The study focuses on cumulative risk assessment (CRA) methodologies for non-dietary exposure to pesticides in agricultural settings. It examines exposure scenarios for operators, re-entry workers, and bystanders, with the aim of assessing the feasibility of using an electronic register of plant protection treatments, known as the Quaderno di Campagna (QdC), to identify pesticide mixtures. The study also seeks to estimate cumulative non-dietary exposure to pesticides associated with craniofacial alterations cumulative assessment groups (CAG-DAC and CAG-DAH), as defined by EFSA.

Data were collected from 385,017 pesticide treatments recorded between 2016 and 2022. These data were primarily sourced from SisCO, a portal where farmers in the Lombardy Region enter information directly, ensuring reliability. Additional details about active substances were obtained from the PESTIDOC database and the Ministry of Health's database of plant protection products (PPPs). The EFSA guidance on cumulative dietary risk assessment for craniofacial alterations served as the reference for substances included in CAG-DAC and CAG-DAH.

Mixture events were identified based on treatments involving active substances from these groups. The QdC data included information on commercial product names, which were linked to their active substances. Mixture events were classified as tank mix applications (multiple substances mixed in a single tank), consecutive applications (sequential use of different PPPs by the same farmer on the same or different areas within the same day), or formulated mixtures (single PPPs containing multiple active substances in the same CAG). Relevant details such as farmer ID, treatment date, area treated, and products used were cross-referenced to identify these events.

Exposure was calculated for operators, re-entry workers, and bystanders using mathematical models tailored to each group. For operators, dermal and inhalation exposure during mixing, loading, and applying pesticides were estimated using the Agricultural Operator Exposure Model (AOEM). Re-entry worker exposure, primarily dermal, was assessed using the Europoem II model, factoring in dermal transfer coefficients, dislodgeable foliar residues, exposure duration, and maximum number of applications. For bystanders, dermal and inhalation exposure from spray drift during application were estimated using a methodology developed by Martin et al. 2008.

Protective factors such as personal protective equipment were considered if specified on product labels.

Several assumptions and limitations were noted. For operators, maximum treated area per entry was used to avoid overestimations. Conservative defaults were applied for dermal absorption and other exposure factors, such as transfer coefficients, dislodgeable residues, and re-entry intervals. However, missing data on the number of operators involved, application methods, and detailed exposure scenarios posed challenges. Additionally, the use of default NOAELs (No Observed Adverse Effect Levels) may have led to overestimated toxicological risks.

The findings revealed that folpet and tebuconazole were the main contributors to cumulative exposure due to their high application rates and low NOAELs for craniofacial alterations. Re-entry workers experienced the highest exposure levels, underscoring the need for targeted risk assessments, particularly for women of childbearing age. The QdC was instrumental in identifying mixture events, crop usage, and treatment frequencies, forming a robust foundation for cumulative exposure characterization.

The method used in this study to estimate non-dietary exposure for different subjects (operator, re-entry worker, and bystander) demonstrates high potential as it allows for exposure estimates that closely reflect real-life situations in agricultural settings. This is achieved by utilizing data that has already been collected and organized in a readily accessible and structured format. Specifically, the electronic register of plant protection treatments (Quaderno di Campagna, QdC) serves as a valuable source of information, enabling the identification of pesticide mixtures and treatment patterns with high precision.

This data source could be further applied to assess the non-dietary exposure component of any pesticide, making it a versatile tool for aggregated exposure for both consumers (in agricultural setting considered as bystanders or resident) and professional users (operators and re-entry workers).

3.2.5.2.2 Pyrethroids, Europe – Occupational environment, Farmers exposure with SPRINT data

Previously, data was collected on pesticide use per farm in the different case-study sites as part of the SPRINT project. The full methodology and data collection that was carried out within SPRINT is described by Mark et al. 2024. In short, data on farm-level pesticide use was collected across the 10 different EU countries included in SPRINT (Spain, Portugal, France, Switzerland, Italy, Croatia, Slovenia, Czech Republic, the Netherlands and Denmark). Farms were selected based on willingness of farmers to participate and the respective key crops grown on these farms. Questionnaires contained questions about activities related to crop protection in detail, e.g., product brand name, target organisms, quantity of product applied, total volume applied and formulation. Between 10 and 19 commercial farms were selected per country, with one or two representative fields selected for each farm. The full dataset can be accessed from https://zenodo.org/records/12526872.

From all pesticides that were applied at the farms, only the pyrethroids were selected. Overall, pyrethroids were applied 35 times across different fields, crop types and countries. The different pyrethroids reported were Alpha-cypermethrin and cypermethrin, deltamethrin, lambda-cyhalothrin and gamma-cyhalothrin, esfenvalerate, pyrethrin, and tau-fluvalinate. An overview of the active ingredients and their brand name as applied can be found in Table 21.

Table 21. Active ingredients reported to be used by farmers in the Mark et al. Publication (collected within SPRINT).

CAS Number	Product	Active Ingredient
91465-08-6	Ampligo	Lambda-cyhalothrin
8003-34-7	Asset Five	Pyrethrin
8003-34-7	CICAPYR	Pyrethrin
52918-63-5	Coraza ec	Deltamethrin
52315-07-8	Cythrin 500 EC	Cypermethrin
52315-07-8	CYTHRINE	Cypermethrin
52315-07-8	Cythrine max	Cypermethrin
52918-63-5	Decis 100 EC	Deltamethrin
52918-63-5	Decis 2,5 EC	Deltamethrin
52918-63-5	Decis Evo	Deltamethrin
52918-63-5	Decis Evo	Deltamethrin
52918-63-5	Delcaps 050 CS	Deltamethrin
52918-63-5	DELTASTAR	Deltamethrin
52918-63-5	Eco-Trap	Deltamethrin
67375-30-8	Fastac	Alpha cypermethrin
67375-30-8	FASTAC 10 EC	Alpha cypermethrin
91465-08-6	Karate Zeon	Lambda-cyhalothrin
91465-08-6	Karate Zeon	Lambda-cyhalothrin
91465-08-6	Karate Zeon	Lambda-cyhalothrin
8003-34-7	Kenpyr	Pyrethrin
8003-34-7	KLARTAN Smart	Pyrethrin
8003-34-7	Krisant EC	Pyrethrin
91465-08-6	KUSTI	Lambda-cyhalothrin
67375-30-8	Mageos	Alpha cypermethrin
91465-08-6	Manto	Lambda-cyhalothrin
91465-08-6	Markate 50	Lambda-cyhalothrin
102851-06-9	Mavrik	Tau-fluvalinate

52918-63-5	Meteor	Deltamethrin
76703-62-3	Nexide	Gamma-cyhalothrin
91465-08-6	Ninja	Lambda-cyhalothrin
8003-34-7	Pirecris	Pyrethrin
8003-34-7	PYREVERT	Pyrethrin
76703-62-3	Rapid	Gamma-cyhalothrin
52918-63-5	Rotor Super	Deltamethrin
66230-04-4	Sumi-alpha 2.5 ec	Esfenvalerate
66230-04-4	Sumicidin Super	Esfenvalerate
102851-06-9	Talita	Tau-fluvalinate
52918-63-5	VIVATRINE EW	Deltamethrin

For calculation of non-dietary exposure, the OPEX calculator can be used (Bemelmans, Varewyck, and Verbeke 2025). The calculator can be applied to calculate (non-dietary) exposure of workers, residents or bystanders. For data entry, a combination of the real-life data on pesticide use per farm from SPRINT will be combined with information from the label and EFSA conclusions to provide input on substance properties for the model.

The scenario modelled will be dependent on the type of crop used, but only outdoor scenarios with downward should be assumed based on the crops included in the study (potatoes, vegetables, fruits, olives, arable crops with focus on cereals and oil seed plants). Since the application equipment is not known, two calculations will be done per field; one assuming vehicle mounted drift-reduction, and one manual-hand held.

The results from the calculator will provide information on whether exposure of workers, bystanders or residents exceeds the set ARfD or AOEL. This risk assessment will add information, as exposure calculations were not included in SPRINT for this dataset. It calculates the 75th percentile for multiple groups, such as resident or child, and different activities such as entry into treated crops and taking into account dermal, ingestion or inhalation routes.

3.2.5.2.3 Pyrethroids, Europe – Occupational environment, Exposure to pyrethroids by veterinary uses

This case study is carried out by a collaboration between ISCIII, ICPS and ANSES

For this case study, two distinct exposure scenarios have been established:

Occupational Exposure – Animal Shelter: Higher exposure occurs during the application of the veterinary product. At the arrival to the shelter of unprotected rescued dogs, the worker will oversee applying the veterinary products to the animal. In this scenario, IPEs are assumed to be used by the worker.

Occupational Exposure – Dog Sitter: Increased exposure takes place during the post-application phase. On the contrary, since no application phase is considered in this scenario, it is assumed that the adult won´t be protected with any IPE.

Both scenarios were developed in accordance with the EMA Guideline on User Safety of Topically Administered Veterinary Medicinal Products (EMA 2018), which applies exclusively to pets, with dogs serving as the focus of this study.

The study examines two pyrethroids, Permethrin and Deltamethrin. Information regarding their use and application was sourced from the national authorities responsible for registration dossiers and technical sheets in Spain, Italy, and France.

The primary objective of this research is to assess the aggregate and combined exposure to these substances during their use in veterinary products. Moreover, a probability assessment will be implemented, including a sensitivity analysis of the stablished EMA model recommended for these scenarios.

3.2.6 First trials to aggregate General and Occupational exposures with the population based approach (ANSES)

The population-based approach was first tested on French impregnation general population data (Santé Publique France 2012). This work was carried out in parallel with the project P4.1.1.4a Feasibility study, described in section 2.2.2. In HBM surveys for the general population, administrated questionnaires include questions on profession, professional sector or the person's knowledge on possible chemical exposure in his/her line of work. The idea was to investigate and identify samples from individuals who declared a specific professional activity and see if their exposure levels were different from the rest of the general population in the ESTEBAN survey (Santé Publique France 2012). To do so, Student t tests were performed to compare means between the specific sample and the total number of samples. Demographic, socio-economic, residential and professional environment data were collected by means of various questionnaires in ESTEBAN. We investigated these data on profession, past employment, professional field and sector to identify French impregnation levels for PFAS, Pyrethroids, Cadmium and Plasticizers. We looked for specific professions such as firefighter, ski waxers, elementary school teachers and farmers. For firefighters, five individuals out of 2503 adults declared this profession in the administrated questionnaires. However, only one sample out of the 5 was analyzed for PFAS concentrations. In France, 0.1% of the population is a professional firefighter (Ministère de l'Intérieur 2023). In ESTEBAN, this proportion was also represented with 0.2% of the sampling size. Regarding ski waxers, no data was available in the ESTEBAN survey. For other professions, it was the same outcome: a few samples out the identified individuals were analyzed for pyrethroids and plasticizers. T tests resulted in no significant difference between the subgroups and the general population. Overall, it would be difficult to apply the population-based approach using HBM data from French general population.

4 Output for risk assessors and managers

Currently, chemical risk assessment within the European Food Safety Authority (EFSA), the European Chemical Agency (ECHA) and the EU Member States mainly relies on the assessment of individual substances or in a few cases mixtures of substances from the same chemical families. In addition, due to specific regulations and agency organization, sources of exposures are assessed separately following different methodologies and data. EFSA focusses on dietary exposure whereas ECHA assessment is related to consumer products, articles, biocide usages, etc. Also, except for pesticides, due to the specificities of occupational situations and separate regulation, exposure and risk assessment in general and occupational environments are in general performed independently in regulatory processes. However, for some chemicals, such as PFAS, heavy metals, pesticides, bisphenols, phthalates, considering exposures from both general and occupational environment, can make the difference regarding the relative significance of exposure sources, routes, exposure pattern (e.g., chronic, sub-chronic or acute exposure) and consequently, the risk. With the development of the Chemical Strategy for Sustainability (CSS), several regulatory reforms are under implementation to account for the multiple exposure from multiple sources and routes. One key deliverable of the CSS, is the 'one substance, one assessment' package, which aims to reallocate between four EU agencies, significant tasks, ensuring coherent and transparent safety assessments of chemicals used in products such as medical devices, toys, food, pesticides and biocides. It aims to streamline and harmonize risk evaluations, avoiding duplication across different agencies and regulations." This reform will enhance data collection, sharing and harmonization between EU agencies with the development of a Common Data Platform. It is also stated that EEA is responsible to collect, host, and maintain HBM data generated in Europe. In addition, EFSA prioritized advancing aggregate exposure assessments covering all relevant sources and routes of exposure to chemicals through the ExpoAdvance project. This project aims to develop a roadmap for harmonized methodology and regulatory guidance in collaboration with European and international partners (EFSA, Cascio, et al. 2022).

The output of this PARC A6.2.1 activity and associated projects contributes to provide a better understanding of the main exposure sources and routes in general and occupational environments, in integrating the modelling of the fate of the substance from its source(s) of emission to its source(s) and route(s) of exposure to support effective exposure and risk management measures. This work aims to provide data, models and operational tools to move away from a compartmentalized view of risk assessment, and to facilitate comparisons between exposure sources and environments and, ultimately, to prioritize areas for action and prevention. Moreover, the projects aim to link external exposure from several sources and routes with the internal doses observed with HBM data. Comparison between internal doses with simulated exposure in applying PBK models developed in PARC P6.2.2 PBK model projects to external exposure sources makes it possible to evaluate the quality of the aggregate exposure models and of the input data. Indeed, executing a proper aggregate exposure assessment requires the combination of heterogeneous data (observations/modelled distributions, different regions, years, populations, etc.), the use of different exposure models (level of details, level of conservatism, type of population groups, regulatory focus, way to integrate variability, uncertainty, etc.). The combination of heterogenous data and models cumulates the uncertainty related to all the input data and models. Thus, in order to provide aggregate exposure for regulatory purposes, it is important to propose approaches, that make it possible to integrate variability and uncertainty and to compare simulated results to observed data such as HBM data. This work also enables to interpret HBM data in terms of sources and routes of exposure to provide targeted management options. Until today, risk assessment is performed using external exposure data source by source. But, now with the development of the Common Data Platform, and the ambition to consider aggregate exposure, HBM data will be more and more often used in risk assessment.

In the occupational scenarios of this deliverable, exposure was estimated based on a combination of measured and modelled data claiming attention for the importance of having sufficient contextual data to support the interpretation of both datasets but also to identify the limitations of each. Modelling is often used in REACH for the assessment of exposure to workers and there are several occupational exposure models available for this purpose. Since many occupational models are designed to provide a conservative estimate in order to protect the workers, merging their output may result in an overconservative aggregated exposure estimate. Thus, it is important to evaluate the prediction of these models in comparing simulated data with measured ones. This will give an estimate of the degree of conservatism of current regulatory risk assessment. However, it is important to notice that some of the occupational datasets were obtained before the most recent regulatory actions were in place, and thus might not represent the actual situation concerning exposure.

The data collection, the methodological developments, their implementation in the PARC model network with T8.3, the first results of the case studies are described in this deliverable to show the advancements made in PARC to develop aggregate exposure assessment. Next steps of the project involve further elaboration of cases studies, verification of model predictions using PBK models from T6.2.2 and HBM data, demonstrating the methodological approach and the use of the operational tools from the PARC model network. The last year of the project will be also dedicated to develop and support the relevance of aggregate exposure assessment in regulatory context and how to better account for regulatory user perspective. Trainings and in-depth discussions with EU agencies EFSA, EEA and ECHA are foreseen to transfer the scientific knowledge to regulatory assessment in an operationalized way. We will continue the discussions started this year 3 during several events and meetings with EU agencies to work toward a routine implementation of the aggregate and mixture risk assessment, the use of HBM data in risk assessment and to reenforce collaborations between EU agencies around these goals.

In conclusion, the output of these A6.2.1 projects, even at their early stage, promote the development of exposure modelling methods for estimating human exposure to chemicals in the field of regulatory and academic chemical risk assessment. It provides incentives for harmonization and policy coordination on the level of sectoral legislations, and push for scientific and structural reforms to develop integrative approaches in member states and EU agencies and regulations.

5 Annex

5.1 Exposure to PFAS from Occupational environment to develop the worker-based approach, case studies (TNO, TTL)

5.1.1 PFAS, Europe - Occupational environment, Chrome platers

Exposure of chrome bath plating was identified as a potential exposure source for PFAS. Elevated levels for PFBS, PFHxS, PFHpS and PFOS were detected especially in Belgian platers and welders. Although, based on the information received from the companies, PFAS mist suppressants were not anymore used, therefore, the exposure may have represented exposure from the earlier use. Alternative PFAS compound, 6:2 FTS (6:2-fluorotelomersulfonic acid) which breaks down to PFHxA is however still commonly used in plating. The first version of the exposure scenario was developed for manual chrome bath plating and automatic chrome bath plating to model potential/previous exposure to PFAS mist suppressants.

Exposure scenario for chrome platers: Table 22 presents the general description of exposure situation as well as the exposure scenario and their determinants.

Table 22. General description of exposure situation.

Product/ exposing material	Supplier	Substance name	CAS number	Molecular weight (g/mol)	Physical state	Vapor pressure in 20°C/Pa	Dustiness (coarse, medium, fine)	Concentration of the substance in product or exposing material (%)
Fluorosurfactants in chrome plating process	-	PFOS	1763-23-1	500,13	liquid	3.31x10-4	-	**0.005%** (0,04-0,06 grams surfactant added to 1 L of chrome plating solution)
Fluorosurfactants in chrome plating process		C16H20F17 NO3S Tetraethylammonium heptadecafluorooctanesulphonate (PFOS salt)	56773-42-3	629,37	solid	-	fine	**0.005%** (0,04-0,06 grams surfactant added to 1 L of chrome plating solution)
Currently commonly used (in Finland): Fluorosurfactants in chrome plating process (Proquel OF) (Ankordyne 30 MS)	KIESOW DR.BRINKMANN GmbH &bCo. KG Bang & Bonsomer Group Oy	6:2 FTS (6:2-fluorotelomersulfonic acid (breaks down to PFHxA etc.)	27619-97-2	428,16	liquid	2.3x10^3, boiling point 100C	-	**0.005-0.05%** (1-5% of 6:2FTS in surfactant solution. 0.5 to 1 L of surfactant added to 9000L of chrome plating solution. Solutions are well mixed.)

(Macuplex str npfx)								

Table 23. Exposure scenario of chrome plating, loading with cranes.

Chrome plating, loading with cranes (manual plating)	
Description of activities	The operator loads the jigs manually and move the objects in to and out from baths with cranes (skin exposure). Formation of mist/droplets to air from electrolyte solution while loading jigs (inhalation exposure potential), Addition of chemicals to baths (very short activity)
General ventilation	yes
Local ventilation	yes
Respiratory protective equipment	Mostly no RPE, but also: TH2 powered fan with ABEK2-P3 filters or FFA2P3D half mask
Work clothing and use of protective gloves	Nitrile or PVC gloves when handling liquids, otherwise leather-textile work gloves, normal work clothing
Room temperature	normal room temperature (10-25 °C)
Room size (small, medium, large)	large
Time (hours) used for the activity per day	8 h
Other relevant parameters	baths covered with lids when not loading/unloading (cannot be used with all objects), process temperature 50-60 °C (elevated from room temperature), foam and plastic balls on the liquid surface of baths, use of mist suppressants (include PFAS), premises and equipment regularly cleaned and maintained, near-field exposure / source at breathing zone during manual work

Table 24. Exposure scenario of automatic chrome plating.

Automatic chrome plating	
Description of activities	objects are hung up to the racks and transferred to the beginning of the processing line. Plating is fully automatized (hoists). When the process is completed, objects are taken from the racks and packed, Addition of chemicals to baths (very short activity)
General ventilation	yes
Local ventilation	yes, sides of the baths have suction
Respiratory protective equipment	Mostly no RPE
Work clothing and use of protective gloves	Cotton gloves normal work clothing
Room temperature	normal room temperature (10-25 °C)
Room size (small, medium, large)	large
Time (hours) used for the activity per day	8 h
Other relevant parameters	process temperature 50-60 °C (elevated from room temperature), foam and plastic balls on the liquid surface of baths,

	use of mist suppressants (include PFAS), premises and equipment regularly cleaned and maintained, far field exposure

Model selection: From the model selection presented in section 2.3, the following models described in Table 25.**Erreur ! Source du renvoi introuvable.** to model the exposure to PFOS for different scenarios of exposure of chrome platers Dermal exposure modeling has not been performed yet.

Table 25. Model selection for PFAS case studies.

Scenario	**Model**	**Justification**
PFOS (liquid): Chrome plating - loading with cranes (manual plating)	ART - The Advanced Reach Tool (version 1.5)	Validity, Matching and Performance OK (model calibrated for liquid mists)
C16H20F17NO3S (solid): Chrome plating - loading with cranes (manual plating)	ART - The Advanced Reach Tool (version 1.5)	Validity, Matching and Performance OK (model calibrated for liquid mists containing powder)
6:2 FTS (solid): Chrome plating - loading with cranes (manual plating)	ART - The Advanced Reach Tool (version 1.5)	Validity, Matching and Performance OK (model calibrated for liquid mists containing powder)
PFOS (liquid): Chrome plating - Automatic	ART - The Advanced Reach Tool (version 1.5)	Validity, Matching and Performance OK (model calibrated for liquid mists)
C16H20F17NO3S (solid): Chrome plating - Automatic	ART - The Advanced Reach Tool (version 1.5)	Validity, Matching and Performance OK (model calibrated for liquid mists containing powder)
6:2 FTS (solid): Chrome plating - Automatic	ART - The Advanced Reach Tool (version 1.5)	Validity, Matching and Performance OK (model calibrated for liquid mists containing powder)

5.2 Exposure to Cadmium from Occupational environment, case studies (TTL, TNO, UNISANTE, ENSP-UNL, STAMI, IVL, LNS, ANSES, INRS,)

5.2.1 Cadmium, Europe – Occupational environment, Maintenance work in power plant boiler– inhalation exposure

Finnish research data (2010-2011) was used to develop exposure scenarios from the exposure to Cd in ash at power plant. Exposure is modeled based on two exposure scenarios: ash removal in power plant boiler and maintenance work in power plant boiler. Here, the exposure scenario of the maintenance work is described. First, a general description of exposure situation (Table 26) is described including detailed information about exposing substances and its character. Secondly, the exposure scenario (Table 27) is described including description of the activities during the work task, working time, ventilation, personal protective equipment, and other working conditions. Based on this information modelers could build a modelling of the exposure scenario.

Exposure scenario for ash removal: Table 26 presents the description of exposure scenario and their determinants.

Table 26. General description of exposure situation.

Product/ exposing material	Supplier	Substance name	CAS number	Molecular weight (g/mol)	Physical state	Vapor pressure in 20°C/Pa	Dustiness (coarse, medium, fine)	Concentration of the substance in product or exposing material (%)
Ash at biomass-fired power plant	-	Cadmium	7440-43-9	112,41	solid	-	fine	Peat < 0,00015 Wood pellets < 0,0015 Wood < 0,0030 REF < 0,0045

Table 27. Exposure scenario of maintenance work in power plant boiler**.**

Maintenance work in power plant boiler	
Description of activities	The operator fixes the boiler (for example, welding, flame cutting and angle grinding)
General ventilation (ventilation rate if available)	Keep the bottom hatches of boiler open to create ventilation inside the boiler
Local ventilation (ventilation rate if available)	None
Respiratory protective equipment	Powered air respirator with ABEK+P3 cartridges
Work clothing and use of protective gloves	Hooded one-piece coveralls, over-wrist long leather gloves
Room temperature	20-40 C
Room size (small, medium, large, dimensions if available m^3)	small to large
Time (hours) used for the activity per day	4-12
Other relevant parameters	Surfaces inside the boilers are still covered with ash dust and metals when maintenance work starts. Surface dust (sulphur content) and hot maintenance methods (welding, flame cutting, and angle grinding) may produce also other gases to boiler air SO_2, NO, NO_2. Maintenance worker should use carbon monoxide gas monitor during working inside power plant boiler. Worker should wash their hands before eating drinking or smoking, and these activities are prohibited inside the boiler. Exposure assessment of worker to Cd (if needed): The urine biomonitoring samples, immediately after workday.

Model selection and results: External exposure model selection has been made according to steps of the model selection-description algorithm and suitable model for inhalation exposure is ART.

5.2.2 Cadmium, Europe – Occupational environment, Silver-Cadmium soldering (hard soldering)

Finnish research data (2005-2008) was used to develop exposure scenarios from the exposure to Cd in silver-cadmium soldering. First, a general description of exposure situation (Table 28) is described including detailed information about exposing substances and its character. Secondly, the exposure scenario (Table 29) is described including description of the activities during the work task, working time, ventilation, personal protective equipment, and other working conditions. Based on this information modelers could build a modelling of the exposure scenario.

Exposure scenario for Sliver-cadmium soldering: Table 28 and Table 29**Erreur ! Source du renvoi introuvable.** present the general description of exposure situation as well as the exposure scenario and their determinants.

Table 28. General description of exposure situation.

Product/exposing material	Supplier	Substance name	CAS number	Molecular weight (g/mol)	Physical state	Vapor pressure in 20°C/Pa	Dustiness (coarse, medium, fine)	Concentration of the substance in product or exposing material (%)
Silver-Cadmium solder		Cadmium	7440-43-9	112,41	fume	-	fine	up to 25 %, approx. 20 %

Table 29. Exposure scenario of silver-cadmium soldering.

Silver-Cadmium soldering (hard soldering)	
Description of activities	manual soldering of electrical components with flame or handheld soldering iron, temperature of the solder 450-800 °C
General ventilation (ventilation rate if available)	Yes
Local ventilation (ventilation rate if available)	Usually yes, efficiency not known
Respiratory protective equipment	Sometimes used, type not known
Work clothing and use of protective gloves	Normal work clothing (coveralls)
Room temperature	Normal room temperature
Room size (small, medium, large dimensions if available m^3)	Medium
Time (hours) used for the activity per day	8h
Other relevant parameters	Process temperature 450-800 °C Cd Melting point 321°C Cd Boiling point Cd 766.8°C Exposure to Ag-Cd solder is relevant nowadays in situations where old seams are being fixed or maintained. Ag-Cd soldering technique not used anymore.

Model selection and results: External exposure model selection has been made according to steps of the model selection-description algorithm and a suitable model for inhalation and dermal exposure is MEASEv1 (Excel).

5.2.3 Cadmium, Europe – Occupational environment, Manual glass manufacturing – preparing red colored batch

Finnish research data (2005-2008) was used to develop exposure scenarios from the exposure to Cd in glass manufacturing. Exposure in manual glass manufacturing is modeled based on three exposure scenarios: Preparing red colored batch, melting of batch and blowing or pressing of glass products. Here, the exposure scenario preparing red colored batch is described.

First, a general description of exposure situation (Table 30) is described including detailed information about exposing substances and its character. Secondly, the exposure scenario (Table 31) is described including description of the activities during the work task, working time, ventilation, personal protective equipment, and other working conditions. Based on this information modelers could build a modelling of the exposure scenario.

Exposure scenario for Manual glass manufacturing-preparing red colored batch: Table 30 and Table 31 present the general description of exposure situation as well as the exposure scenario and their determinants.

Table 30. General description of manual glass manufacturing.

Product/ exposing material	Supplier	Substance name	CAS number	Molecular weight (g/mol)	Physical state	Vapor pressure in 20°C/Pa	Dustiness (coarse, medium, fine)	Concentration of the substance in product or exposing material (%)
Glass batch		Cadmium	7440-43-9	112,41	solid	-	fine	<1%
Melted glass		Cadmium	7440-43-9	112,41	fume	-		<1%

Table 31. Exposure scenario of manual glass manufacturing.

Manual glass manufacturing – preparing red colored batch	
Description of activities	Measuring, pouring and mixing of solid raw materials to pots (fine powder)
General ventilation (ventilation rate if available)	Effective general ventilation (used primarily to lower the ambient air temperature)
Local ventilation (ventilation rate if available)	No
Respiratory protective equipment	No
Work clothing and use of protective gloves	Overalls, leather/textile gloves
Room temperature	30 °C
Room size (small, medium, large, dimensions if available m^3)	Medium
Time (hours) used for the activity per day	5 (normal working day, but extra breaks due to warm conditions)
Other relevant parameters	Near field exposure Exposure to fine solids Batch dust may spread to floors

Model selection and results: External exposure model selection has been made according to steps of the model selection-description algorithm and a suitable model for inhalation exposure is TREXMO (ECETOC TRAv3, EASEv2) and for dermal exposure is dART. Modelling has been conducted by two experienced modelers. There were modeler specific differences in the results. To reduce variation between the modelers, modelers have been working the scenario description to be more specific. Following more detailed scenario description new modellings will be made before continuing into next step.

5.2.4 Cadmium, Europe – Occupational environment, Manual glass manufacturing – melting of batch

Finnish research data (2005-2008) was used to develop exposure scenarios from the exposure to Cd in glass manufacturing. Exposure in manual glass manufacturing is modeled based on three exposure scenarios: Preparing red colored batch, melting of batch and blowing or pressing of glass products. Here, the exposure scenario melting of batch is described.

First, a general description of exposure situation (Table 32) is described including detailed information about exposing substances and its character. Secondly, the exposure scenario (Table 32) is described including description of the activities during the work task, working time, ventilation, personal protective equipment, and other working conditions. Based on this information modelers could build a modelling of the exposure scenario.

Exposure scenario for Manual glass manufacturing-melting of bash: Table 32**Erreur ! Source du renvoi introuvable.** presents the general description of exposure situation.

Table 32. Exposure scenario of manual glass manufacturing.

Manual glass manufacturing – melting of batch	
Description of activities	Moving pots containing moisturized batch manually near the ovens, measuring batch to melting pots small amount at the time, and melting of the mixture in 1360-1380 C
General ventilation (ventilation rate if available)	Effective general ventilation (used primarily to lower the ambient air temperature)
Local ventilation (ventilation rate if available)	Yes, ovens have exhausts
Respiratory protective equipment	Some workers may use powered RPE
Work clothing and use of protective gloves	Overalls, leather/textile gloves
Room temperature	30 °C
Room size (small, medium, large, dimensions if available m^3)	Medium
Time (hours) used for the activity per day	5 (normal working day, but extra breaks due to warm conditions)
Other relevant parameters	Near field exposure Exposure to fumes Hot conditions, physically demanding work

Model selection and results: External exposure model selection has been made according to steps of the model selection-description algorithm and a suitable model for inhalation and dermal exposure is MEASEv1(excel sheet).

5.2.5 Cadmium, Europe – Occupational environment, Glass manufacturing - blowing or pressing of glass products

Finnish research data (2005-2008) was used to develop exposure scenarios from the exposure to Cd in glass manufacturing. Exposure in manual glass manufacturing is modeled based on three exposure scenarios: Preparing red colored batch, melting of batch and blowing or pressing of glass products. Here, the exposure scenario melting of batch is described.

First, a general description of exposure situation (Table 30) is described including detailed information about exposing substances and its character. Secondly, the exposure scenario (Table 33) is described including description of the activities during the work task, working time, ventilation, personal protective equipment, and other working conditions. Based on this information modelers could build a modelling of the exposure scenario.

Exposure scenario for Glass manufacturing - blowing or pressing of glass products: Table 33 presents the description of exposure scenario.

Table 33. Exposure scenario of manual glass manufacturing.

Manual glass manufacturing - blowing or pressing of glass products

Description of activities	Carrying melted glass into process, making glass objects by pressing or blowing, moving objects to finalization, carrying melted material to pressing and blowing area. Blowers do not do other tasks. Everyone is working closely together and therefore being exposed to similar levels of fumes.
General ventilation (ventilation rate if available)	Effective general ventilation (used primarily to lower the ambient air temperature)
Local ventilation (ventilation rate if available)	No
Respiratory protective equipment	No
Work clothing and use of protective gloves	Overalls, no gloves
Room temperature	30 °C
Room size (small, medium, large, dimensions if available m^3)	Medium
Time (hours) used for the activity per day	5 (normal working day, but extra breaks due to warm conditions)
Other relevant parameters	Near field exposure Exposure to fumes Hot conditions, physically demanding work

Model selection and results: External exposure model selection has been made according to steps of the model selection-description algorithm and a suitable model for inhalation and dermal exposure is TREXMO(MEASEv1) or MEASEv1(Excel sheet).

5.2.6 Cadmium, Europe – Occupational environment, E-waste workers: Exposure to Cd in batteries recycling

HBM4EU (2017-2022) was used to develop exposure scenarios from the exposure to Cd in battery recycling. Exposure in battery recycling is divided into two separate scenarios lead battery recycling and nickel-cadmium batteries recycling. Currently, lead battery recycling exposure scenario is further developed and modelled. It has been also estimated that lead battery recycling exposure scenario can be expanded into the nickel-cadmium battery recycling workers and this work is still ongoing.

First, a general description of exposure situation (Table 30) is described including detailed information about exposing substances and its character. Secondly, the exposure scenario (Table 34) is described including description of the activities during the work task, working time, ventilation, personal protective equipment, and other working conditions. Based on this information, modelers could build a modelling of the exposure scenario.

Exposure scenario for E-waste workers: Table 34 and Table 35**Erreur ! Source du renvoi introuvable.** present the general description of exposure situation as well as the exposure scenario and their determinants.

Table 34. General description of exposure situation.

Product/ exposing material	Supplier	Substance name	CAS number	Molecular weight (g/mol)	Physical state	Vapor pressure in 20°C/Pa	Dustiness (coarse, medium, fine)	Concentration of the substance in product or exposing material (%)
Cd in lead batteries	-	Cadmium	7440-43-9	112,41	solid	-	Fine and medium	0.002 to 1.0% <0.002%
Cd in NiCd batteries	-	Cadmium	7440-43-9	112,41	solid	-	Fine and medium	3-28%

Table 35. Exposure scenario of furnace operator.

Furnace operator	
Description of activities	Ensures timely preparation of furnace loads. Executes the load. Monitors furnace and filter parameters. Ensures the conditions of the unloading and demolding (lead/slag)
General ventilation (ventilation rate if available)	Open door and some exhaust mechanical devices
Local ventilation (ventilation rate if available)	None
Respiratory protective equipment	Electric Supplied Air Fed Full Face Gas Face Cover Constant Flow Respirator System Device
Work clothing and use of protective gloves	Full cover of the working clothes with disposal suit, over-wrist long leather gloves
Room temperature	+ 40º C
Room size (small, medium, large, dimensions if available m^3)	Large hall
Time (hours) used for the activity per day	8-12
Other relevant parameters	Worker should wash their hands before eating drinking or smoking, and these activities are prohibited inside the working hall. Disposal suit removed when leaving the hall. RPE pieces are not cleaned regularly Near-field exposure / source at breathing zone can happen since RPE showed contamination and it's not cleaned regularly. Far-field exposure / source at breathing zone can also happen since the workplace environment has some environmental contamination and dust is resuspended. Worker should wash their hands before eating drinking or smoking, and these activities are prohibited inside the working hall. Disposal suit removed when leaving the hall. RPE pieces are not cleaned regularly

Model selection and results: External exposure model selection has been made according to steps of the model selection-description algorithm and a suitable model for dermal exposure is dART. Model selection of inhalation exposure has not been performed yet.

5.3 Exposure to Chromium from Occupational environment, case studies (TTL, TNO, UNISANTE, ENSP-UNL, STAMI, IVL, LNS, ANSES, INRS)

5.3.1 Chromium, Europe – Occupational environment, Chrome plating - loading with cranes (manual plating)

HBM4EU (2017-2022) was used to develop exposure scenarios from the exposure to CrVI in chrome plating. Chrome plating work can be divided into three different exposure scenarios: manual chrome plating where loading is performed with cranes, automatic chrome plating, dry grinding which is manual process, and automatic wet grinding. Here, manual chrome plating (loading with cranes) exposure scenario is described in detail.

First, a general description of exposure situation (Table 36) is described including detailed information about exposing substances and their character. Secondly, the exposure scenario (Table 37) is described including description of the activities during the work task, working time, ventilation, personal protective equipment, and other working conditions. Based on this information, modelers could build a modelling of the exposure scenario.

Multiple tasks were identified to be relevant for chrome exposure during electroplating. Such tasks were split up for modelling and consisted of manual plating, automatic plating and grinding.

Exposure scenario for Chrome plating - loading with cranes: Table 36 and Table 37**Erreur ! Source du renvoi introuvable.** present the general description of exposure situation as well as the exposure scenario and their determinants.

Table 36. General description of exposure situation.

Product/ Exposing material	Supplier	Substance name	CAS number	Molecular weight (g/mol)	Physical state	Vapor pressure in 20°C/Pa	Dustiness (coarse, medium, fine)	Concentration of the substance in product or exposing material (%)	Amount of product or exposing material used (kg or Liter or kg/min)
CrVI in chrome plating process, plating	-	Hexavalent chromium	7440-47-3	51,9961	liquid	Melting point 1907°C, boiling point 2671°C	-	CrO_3 10-50 %	
CrVI in chrome plating process, grinding	-	Hexavalent chromium	7440-47-3	51,9961	solid	-	fine	CrO_3 10-50 %	

Table 37. Exposure scenario of chrome plating, loading with cranes.

Chrome plating - loading with cranes (manual plating)	
Description of activities, exposure pathways	The operator loads the jigs manually and move the objects in to and out from baths with cranes (skin exposure). Formation of mist/droplets to air from electrolyte solution while loading jigs (inhalation exposure potential). Addition of chemicals to baths (very short activity)
General ventilation (ventilation rate if available)	yes
Local ventilation (ventilation rate if available)	yes (fixed capturing hood-type)
Respiratory protective equipment	Mostly no RPE, but also: TH2 powered fan with ABEK2-P3 filters or FFA2P3D half mask
Work clothing and use of protective gloves	Nitrile or PVC gloves when handling liquids, otherwise leather-textile work gloves normal work clothing
Room temperature	normal room temperature (10-25 °C)
Room size (small, medium, large, dimensions if available m^3)	large
Time (hours) used for the activity per day	8 h
Other relevant parameters	baths covered with lids when not loading/unloading (cannot be used with all objects), baths ca. 5-10 meters long, and ca. 1-3 meters wide. Process temperature 50-60 °C (elevated from room temperature). Foam and plastic balls on the liquid surface of baths. Use of mist suppressants (include PFAS). Premises and equipment regularly cleaned and maintained. Near-field exposure / source at breathing zone during manual work

Model selection and results: External exposure model selection has been made according to steps of the model selection-description algorithm and a suitable model for inhalation exposure is ART and for dermal exposure dART.

Modelling has been conducted by two experienced modelers. There were modeler specific differences in the results. To reduce variation between the modelers, modelers have been working the scenario description to be more specific. Following more detailed scenario description new modellings will be made.

5.3.2 Chromium, Europe – Occupational environment, Chrome plating - Automatic

HBM4EU (2017-2022) was used to develop exposure scenarios from the exposure to CrVI in chrome plating. Chrome plating work can be divided into four different exposure scenarios: manual chrome plating where loading is performed with cranes, automatic chrome plating, dry grinding which is manual process, and automatic wet grinding. Here, automatic chrome plating exposure scenario is described in detail.

First, a general description of exposure situation (Table 36) is described including detailed information about exposing substances and their character. Secondly, the exposure scenario (Table 38) is described including description of the activities during the work task, working time, ventilation, personal protective equipment, and other working conditions. Based on this information, modelers could build a modelling of the exposure scenario.

Exposure scenario for Chrome plating - Automatic: Table 38 presents the description of exposure scenario and their determinants.

Table 38. Exposure scenario of automatic chrome plating.

Chrome plating - Automatic	
Description of activities	objects are hung up to the racks and transferred to the beginning of the processing line manually. Plating itself is fully automatized (hoists). When the process is completed, objects are manually taken from the racks and packed. Addition of chemicals to baths (very short activity)
General ventilation (ventilation rate if available)	yes
Local ventilation (ventilation rate if available)	yes, sides of the baths have suction (fixed capturing hood-type)
Respiratory protective equipment	Mostly no RPE
Work clothing and use of protective gloves	Cotton gloves normal work clothing
Room temperature	normal room temperature (10-25 °C)
Room size (small, medium, large, dimensions if available m^3)	large
Time (hours) used for the activity per day	8 h (approx. 30% of time in process environment, 70% in a control room)
Other relevant parameters	process temperature 50-60 °C (elevated from room temperature), baths ca. 5-10 meters long, and ca. 1-3 meters wide. Foam and plastic balls on the liquid surface of baths. Use of mist suppressants (include PFAS). Premises and equipment regularly cleaned and maintained. Far field exposure

Model selection and results: External exposure model selection has been made according to steps of the model selection-description algorithm and a suitable model for inhalation exposure is ART and for dermal exposure dART.

5.3.3 Chromium, Europe – Occupational environment, Chrome plating - Dry grinding, manual

HBM4EU (2017-2022) was used to develop exposure scenarios from the exposure to CrVI in chrome plating. Chrome plating work can be divided into four different exposure scenarios: manual chrome plating where loading is performed with cranes, automatic chrome plating, dry grinding which is manual process, and automatic wet grinding. Here, dry grinding (manual) exposure scenario is described in detail.

First, a general description of exposure situation (Table 36) is described including detailed information about exposing substances and their character. Secondly, the exposure scenario (Table 39) is described including description of the activities during the work task, working time, ventilation, personal protective equipment, and other working conditions. Based on this information, modelers could build a modelling of the exposure scenario.

Exposure scenario for Chrome plating Dry grinding, manual: Table 39**Erreur ! Source du renvoi introuvable.** presents the description of exposure scenario and their determinants.

Table 39. Exposure scenario description of dry grinding (manual).

Dry grinding, manual	
Description of activities	Usually old objects are grinded, before plating
General ventilation (ventilation rate if available)	yes
Local ventilation (ventilation rate if available)	yes
Respiratory protective equipment	no
Work clothing and use of protective gloves	leather-textile work gloves normal work clothing
Room temperature	normal room temperature (20-25 °C)
Room size (small, medium, large, dimensions if available m^3)	large
Time (hours) used for the activity per day	8 h
Other relevant parameters	Work area is well cleaned. Near field exposure

Model selection and results: External exposure model selection has been made according to steps of the model selection-description algorithm and a suitable model for inhalation and dermal exposure is TREXMO(MEASEv1) or MEASEv1 (Excel sheet).

5.3.4 Chromium, Europe – Occupational environment, Chrome plating – Automatic wet grinding

HBM4EU (2017-2022) was used to develop exposure scenarios from the exposure to CrVI in chrome plating. Chrome plating work can be divided into four different exposure scenarios: manual chrome plating where loading is performed with cranes, automatic chrome plating, dry grinding which is manual process, and automatic wet grinding. Here, automatic wet grinding exposure scenario is described in detail.

First, a general description of exposure situation (Table 36) is described including detailed information about exposing substances and their character. Secondly, the exposure scenario (Table 40) is described including description of the activities during the work task, working time, ventilation, personal protective equipment, and other working conditions. Based on this information, modelers could build a modelling of the exposure scenario.

Exposure scenario for Chrome plating Automatic wet grinding: Table 40 presents the description of exposure scenario and their determinants.

Table 40. Exposure scenario description of automatic wet griding.

Automatic wet grinding	
Description of activities	objects are put into the grinding machine and taken out manually, grinding is automated
General ventilation (ventilation rate if available)	yes

Local ventilation (ventilation rate if available)	yes
Respiratory protective equipment	no
Work clothing and use of protective gloves	Disposable nitrile gloves while wet grinding, leather-textile or leather work gloves in other tasks. normal work clothing
Room temperature	normal room temperature (10-25 °C)
Room size (small, medium, large, dimensions if available m^3)	large
Time (hours) used for the activity per day	8 h
Other relevant parameters	Splash shield when grinder is running. Work area is well cleaned. Near field/far-field exposure

Model selection and results: External exposure model selection has been made according to steps of the model selection-description algorithm and a suitable model for inhalation and dermal exposure is TREXMO(MEASEv1) or MEASEv1 (excel sheet). Modelling has been conducted by two experienced modelers. There were modeler specific differences in the results. To reduce variation between the modelers, modelers have been working the scenario description to be more specific. Following more detailed scenario description new modellings will be made.

5.3.5 Chromium, Europe – Occupational environment, Spray painting aircrafts (full body) with paints with chrome

HBM4EU (2017-2022) was used to develop exposure scenarios from the exposure to CrVI in spray painting aircrafts with paints with chrome. Spray painting aircraft can be divided into two exposure scenarios: full body aircraft painting and parts of aircraft painting. Here, spray painting of full body of aircrafts exposure scenario is described in detail.

First, a general description of exposure situation (Table 36) is described including detailed information about exposing substances and their character. Secondly, the exposure scenario (Table 41) is described including description of the activities during the work task, working time, ventilation, personal protective equipment, and other working conditions. Based on this information, modelers could build a modelling of the exposure scenario.

Exposure scenario for Spray painting aircrafts: Table 41 presents the description of exposure scenario and their determinants.

Table 41. Exposure scenario description of spray-painting aircrafts with paint with chrome.

Spray painting aircrafts (full body) with paints with chrome	
Description of activities	The operator applies the paints by spraying in the top and below the aircraft
General ventilation (ventilation rate if available)	yes
Local ventilation (ventilation rate if available)	No
Respiratory protective equipment	RPE used with ABEK2-P3 filters
Work clothing and use of protective gloves	Nitrile or PVC gloves and Tyvek complete suit
Room temperature	normal room temperature (10-25 °C)
Room size (small, medium, large, dimensions if available m^3)	large
Time (hours) used for the activity per day	4 to 6 h (depending on the size of the aircraft)
Other relevant parameters	Paints prepared by other workers; Premises and equipment regularly cleaned and maintained; Near-field exposure / source at breathing zone can happen since sometime workers remove the RPE; Removing the PPE at the end of the work might imply exposure by inhalation (1st thing to be removed is the RPE)

	and by ingestion (hands contaminated touch the face and eyes and RPE).

Model selection and results: External exposure model selection has been made according to steps of the model selection-description algorithm and a suitable model for inhalation exposure is ART and for dermal exposure dART. Modelling has been conducted by two experienced modelers. There were modeler specific differences in the results. To reduce variation between the modelers, modelers have been working the scenario description to be more specific. Following more detailed scenario description new modellings will be made.

5.3.6 Chromium, Europe – Occupational environment, Spray painting aircrafts parts with paints with chrome

HBM4EU (2017-2022) was used to develop exposure scenarios from the exposure to CrVI in spray painting aircrafts with paints with chrome. Spray painting aircraft can be divided into two exposure scenarios: full body aircraft painting and parts of aircraft painting. Here, spray painting of parts of aircrafts exposure scenario is described in detail.

First, a general description of exposure situation (Table 36) is described including detailed information about exposing substances and their character. Secondly, the exposure scenario (Table 42) is described including description of the activities during the work task, working time, ventilation, personal protective equipment, and other working conditions. Based on this information, modelers could build a modelling of the exposure scenario.

Exposure scenario for Spray painting aircrafts parts with paints with chrome : Table 42 presents the description of exposure scenario and their determinants.

Table 42. Exposure scenario of spray-painting aircrafts parts with paint with chrome.

Spray painting aircrafts parts with paints with chrome	
Description of activities	The operator applies the paints by spraying mostly in a closed booth
General ventilation (ventilation rate if available)	yes
Local ventilation (ventilation rate if available)	yes
Respiratory protective equipment	RPE used with ABEK2-P3 filters
Work clothing and use of protective gloves	Nitrile or PVC gloves and Tyvek suit and normal working clothes
Room temperature	normal room temperature (10-25 °C)
Room size (small, medium, large, dimensions if available m^3)	medium
Time (hours) used for the activity per day	8 h
Other relevant parameters	Paints preparations are done by the same workers that apply the paint; Premises and equipment regularly cleaned and maintained; Near-field exposure / source at breathing zone can happen since sometime workers remove the RPE; Far-field exposure / source at breathing zone can also happen since sometimes parts of the aircraft do not fill in the booths and are painted outside the booths;

	Removing the PPE at the end of the work might imply exposure by inhalation (1st thing to be removed is the RPE sometimes still inside the booth) and by ingestion (hands contaminated touch the face and eyes and RPE).

Model selection and results: External exposure model selection has been made according to steps of the model selection-description algorithm and a suitable model for inhalation exposure is ART and for dermal exposure dART. Modelling has been conducted by two experienced modelers. There were modeler specific differences in the results. To reduce variation between the modelers, modelers have been working the scenario description to be more specific. Following more detailed scenario description new modellings will be made.

5.3.7 Chromium, Europe – Occupational environment, Welders

HBM4EU (2017-2022) was used to develop exposure scenario from the exposure to CrVI in welders

First, a general description of exposure situation (Table 43) is described including detailed information about exposing substances and their character. Secondly, the exposure scenario (Table 44) is described including description of the activities during the work task, working time, ventilation, personal protective equipment, and other working conditions. Based on this information, modelers could build a modelling of the exposure scenario.

Exposure scenario for Welders: Table 43 and Table 44, present the description of exposure scenario and their determinants.

Table 43. General description of exposure situation.

Product/exposing material	Supplier	Substance name	CAS number	Molecular weight (g/mol)	Physical state	Vapour pressure in 20°C/Pa	Dustiness (coarse, medium, fine)	Concentration of the substance in product or exposing material (%)	Amount of product or exposing material used (kg or Liter or kg/min)
CrVI in welding	-	Hexavalent chromium	7440-47-3	51,9961	solid	Melting point 1907°C, boiling point 2671°C	Medium to fine	NA	NA

Table 44. Exposure scenario of welding.

Welding	
Description of activities	Manual welding (the most reported welding process was tungsten inert gas (TIG) (39.5%) Normally, TIG welding is performed at temperatures ranging from 5,000 to 20,000 degrees Fahrenheit.
General ventilation (ventilation rate if available)	Natural ventilation only
Local ventilation (ventilation rate if available)	yes, Extracted welding booth

Respiratory protective equipment	Welding helmet with half mask re-usable dust respirator
Work clothing and use of protective gloves	Protective clothing: Fire/flame resistant clothing Welding gloves Workers trained for using the protective clothes
Room temperature	Room temperature
Room size (small, medium, large, dimensions if available m^3)	No data
Time (hours) used for the activity per day	4 to 6 hours
Other relevant parameters	In the case of welding, the levels of total Cr and Cr(VI) were significantly lower in the presence of LEV. Cr(VI) levels are below the proposed BOELV of 5 g/m3. However, the Cr and Cr(VI) levels inside the RPE indicated that exposure to Cr(VI) still occurs (mean value of 1.6 g/m3 and P95 of 4.1 g/m3, with values ranging from 0.1 to 44.3 g/m3), although below the OEL in most of the cases. Workers who had received previous training in OSH issues presented significantly lower total Cr levels in urine and hand wipes, thus emphasising the importance of instruction and training.

Model selection and results: External exposure model selection has been made according to steps of the model selection-description algorithm and a suitable model for inhalation exposure is TREXMO (EASE 2.0) and for dermal exposure MEASEv1 (Excel sheet). Modelling has been conducted by two experienced modelers. There were modeler specific differences in the results. To reduce variation between the modelers, modelers have been working the scenario description to be more specific. Following more detailed scenario description new modellings will be made.

5.4 Exposure to Plasticizers from Occupational environment, case studies (TTL, UNISANTE, ANSES, IVL, ENSP-UNL, WUR, IDAEA-CISC, LNS, RUMC; LNS, INSA, NIJZ, CSTB)

5.4.1 Plasticizers, Europe – Occupational environment, E-waste handlers

HBM4EU (2017-2022) was used to develop exposure scenarios from the exposure to phthalates in batteries recycling. In the exposure scenario batteries braker operates a batteries braker machine that crushes the plastic part of the old batteries.

First, a general description of exposure situation (Table 45) is described including detailed information about exposing substances and their character. Secondly, the exposure scenario (Table 46) is described including description of the activities during the work task, working time, ventilation, personal protective equipment, and other working conditions. Based on this information, modelers could build a modelling of the exposure scenario.

Table 45. General description of exposure situation.

Product/exposing material	Supplier	Substance name	CAS number	Molecular weight (g/mol)	Physical state	Vapor pressure in 20°C/Pa	Dustiness (coarse, medium, fine)	Concentration of the substance in product or exposing material (%)
Phthalates present in the batteries	-	Mono(2-ethyl-5-hydroxyhexyl) phthalate (5OH-MEHP)	40321-99-1	294.34	solid		-	Not known

Table 46. Exposure scenario of batteries recycling.

Batteries recycling – Batteries breaker	
Description of activities	Workers operate a batteries breaker machine that crushes the plastic part of the old batteries
General ventilation	Good general ventilation, machine located outdoor
Local ventilation	No
Respiratory protective equipment	None
Work clothing and use of protective gloves	Working clothes: trousers, shirt, protection shoes, gloves, RPE used infrequently
Room temperature	15-20 C
Room size (small, medium, large)	outdoor
Time (hours) used for the activity per day	6 hours per shift
Other relevant parameters	Biomonitoring data shows that for this and other phthalates levels were higher in pre-shift urine samples than in post-shift samples

Model selection and results: Model selection is under progress.

5.4.2 Plasticizers, Europe – Occupational environment, Plastic products manufacturers

Finnish research data (2014-2016) was used to develop exposure scenarios from the exposure to phthalates in mixing plasticizers to PVC resin and extrusion of plastic products. This is divided into two exposure scenarios manufacturing plastic products by extrusion and manufacturing tarpaulins by extrusion.

First, a general description of exposure situation (Table 47) is described including detailed information about exposing substances and their character. Secondly, the exposure scenario (Table 48) is described including description of the activities during the work task, working time, ventilation, personal protective equipment, and other working conditions. Based on this information, modelers could build a modelling of the exposure

Table 47. General description of exposure situation.

Product/exposing material	Supplier	Substance name	CAS number	Molecular weight (g/mol)	Physical state	Vapor pressure in 20°C/Pa	Dustiness (coarse, medium, fine)	Concentration of the substance in product or exposing material (%)
Plasticizers added into PVC resin -> profiles, tarpaulins, and other components extruded	-	DPHP DINP	53306-54-0 28553-12-0	446 419	liquid	0,0000037 0,000068	-	Harder products may contain less than 20%, but the softer the material produced, more plasticizers are used (up to 50%)

Table 48. Exposure scenario of manufacturing plastic products by extrusion.

Manufacturing plastic products by extrusion (automated)	
Description of activities	Process workers mix, granulate and pack PVC resins and additives. Processes are mostly automated and closed (containers, automatic weighing and mixing). Workers spend

	most time in control rooms, excluding occasional checking and cleaning of the process equipment.
General ventilation	Good general ventilation
Local ventilation	Mostly closed process, local ventilation
Respiratory protective equipment	None
Work clothing and use of protective gloves	Short sleeved T-shirt, leather-textile gloves
Room temperature	20-25 C
Room size (small, medium, large)	large
Time (hours) used for the activity per day	1-2 hours max in other premises than control room
Other relevant parameters	mostly far-field exposure process in elevated temperature, 100-110 C stationary air samples all < LOD, so it may be assumed that most relevant route of exposure is skin.

Model selection and results: External exposure model selection has been made according to steps of the model selection-description algorithm and a suitable model for inhalation exposure is Stoffenmanager. Dermal exposure was modelled using ECETOC TRA. Modelling by second modeler is under progress.

Table 49. Exposure scenario of manufacturing tarpaulins by extrusion.

Manufacturing tarpaulins by extrusion (semi-automatic)	
Description of activities	Workers mix different raw materials and additives to be extruded and spread over the canvas. Machinery needs attention, but not constantly.
General ventilation	Good general ventilation
Local ventilation	local ventilation
Respiratory protective equipment	None
Work clothing and use of protective gloves	Short sleeved T-shirt, leather-textile gloves
Room temperature	20-25 C
Room size (small, medium, large)	large
Time (hours) used for the activity per day	4 hours near the machinery, 4 hours in control rooms
Other relevant parameters	mostly far-field exposure process in elevated temperature, 100-110 C Breathing zone air samples all < LOD, so it may be assumed that most relevant route of exposure is skin.

Model selection and results: External exposure model selection has been made according to steps of the model selection-description algorithm and a suitable model for inhalation exposure is ART and for dermal exposure ECETOC TRA. Modelling by second modeler is under progress.

5.4.3 Plasticizers, Europe – Occupational environment, Daycare and primary school's teachers

French research data (2013-2017) was used to develop exposure scenarios from the exposure to phthalates in school teachers. First, a general description of exposure situation (Table 50) is described including detailed information about exposing substances and their character. Secondly, the exposure scenario (Table 51) is described including description of the activities during the work task, working time, ventilation, personal protective equipment, and other working conditions. Based on this information, modelers could build a modelling of the exposure

Table 50. General description of exposure situation.

Product/exposing material	Supplier	Substance name	CAS number	Molecular weight (g/mol)	Physical state	Vapor pressure in 20°C/Pa	Dustiness (coarse, medium, fine)	Concentration of the substance in product or exposing material (%)
Phthalates present in French nurseries and elementary schools	-	BBP, DBP, DEP, DEHP, DiBP, DiNP			solid		-	Not known

Exposure scenario:

Table 51. Exposure scenario of school teachers.

School teachers exposed to phthalates in French classrooms	
Description of activities	Classrooms with vinyl floorings and other plastics items that cause exposure during school hours
General ventilation	Natural ventilation for most of the classrooms
Local ventilation	No
Respiratory protective equipment	None
Work clothing and use of protective gloves	No
Room temperature	The average and median weekly temperatures are 22.7 and 22.5 °C, respectively
Room size (small, medium, large)	
Time (hours) used for the activity per day	9:00 – 17:00
Other relevant parameters	Phthalate concentrations in the air and dust are available, PM2.5 concentrations are available

Model selection and results: model selection is under progress.

5.5 Source-to-dose model overview

This annex contains two schematic overviews of possible pathways considered in source-to-dose models. Note that whereas the initial focus of the source to dose models was on the first part (from emissions to environmental media), majority of the investaged models also had a subqesuent exposure model (from levels environmental media up to exposure), and hence the latter aspects are also accounted for in this overview. Figure 28 focuses on the pathways between sources and environmental media, while Figure 29 focuses on the pathways from environmental media to human exposure. Table 52 and Table 53 give an overview of which models take which pathways into account, respectively the sources to environmental media and the environmental media to human exposure. Table 54 gives additional information on the considered models, whether the models are dynamic and/or provide only steady state solutions, if they consider different land use scenarios, if they take into account background (=exposure arising from non locally pollution sources, such as exposure through commercial food) , which inputs they need, if they consider different ages or age groups, if they incorporate a PBK module, for which chemicals it has been parameterized, if it provides probabilistic results or point estimates, if the possibility to perform uncertainty or sensitivity analysis is included, how the model is built (e.g. Excel, web app,…) and some remarks about lacking features.

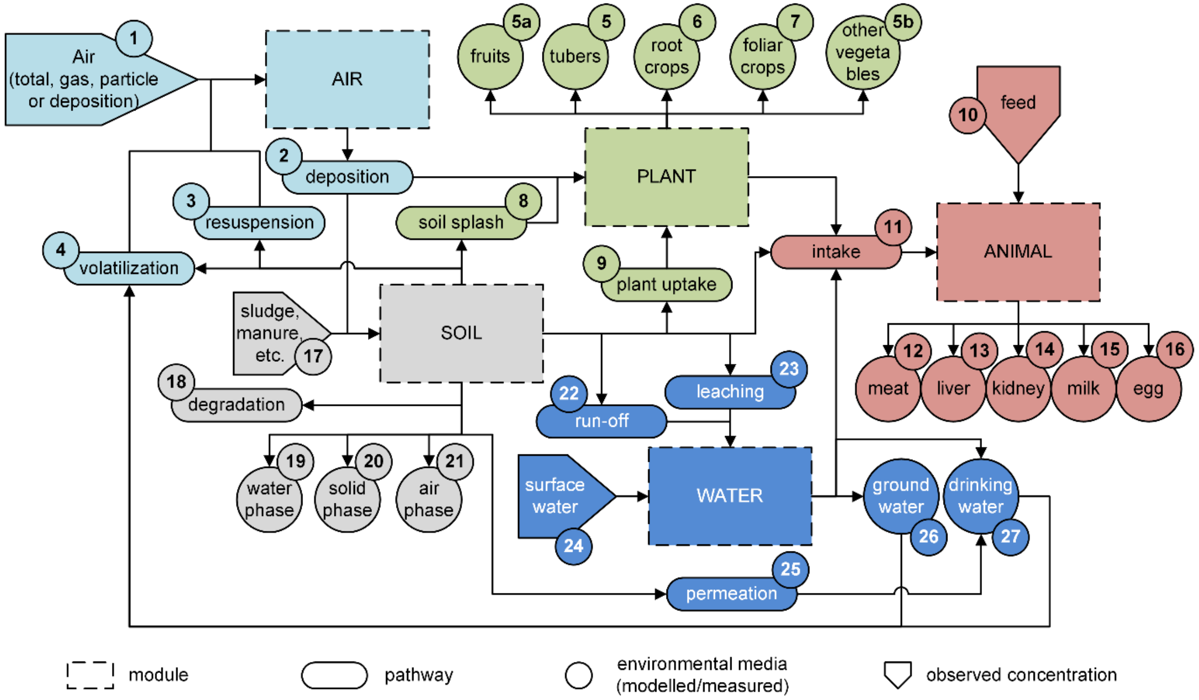


Figure 28. Schematic overview of possible source to environmental media pathways considered in the source-to-dose models.

Table 52. Overview of the models included in the inventory of existing source-to-dose models, where the considered pathways between sources and environmental media are indicated per model. The numbers correspond to the numbers in Figure 28.

Model	Source to environment media – considered pathways/transfer																													
	AIR				PLANT							ANIMAL								SOIL					WATER					
	1	2	3	4	5a	5b	5	6	7	8	9	10	11	12	13	14	15	16		17	18	19	20	21	22	23	24	25	26	27
	Air	Deposition	resuspension	Volatilization	Fruits	Other vegetab.	Tubers	Root crops	Foliar crops	Soil splash	Plant uptake	Feed	Intake	Meat	Liver	Kidney	Milk	Egg	Other	Sludge, manure, …	Degradation	Water phase	Solid phase	Air phase	Run-off	Leaching	Surface water	Permeation	Ground water	Drinking water
EUSES +		x									x			x			x													
MERLIN-Expo				x	x	x		x	x		x			x			x		Fish			x	x				x			x
S-risk		x	x	x	x	x		x	x	x	x	x	x	x	x	x	x	x				x	x	x		x		x	x	x
Cal-Tox		x	x	x							x		x	x			x	x	Fish + sea food											
CSOIL		x	x	x	x	x		x	x		x											x	x	x				x	x	X
Cd mass balance											x															x				
IEUBK																														
PHAGM																														
USEtox PFAS	x	x																			x					x	x			x
SMURF	x	x	x	x																	x				x		x			
CLEA	x			x	x	x		x	x		x																			
Atlantic RBCA				x							x		x									x	x	X						
HOUGH			x	x							x		x	x		x														
RISKNET	x		x	x																		x	x	x		x			X	

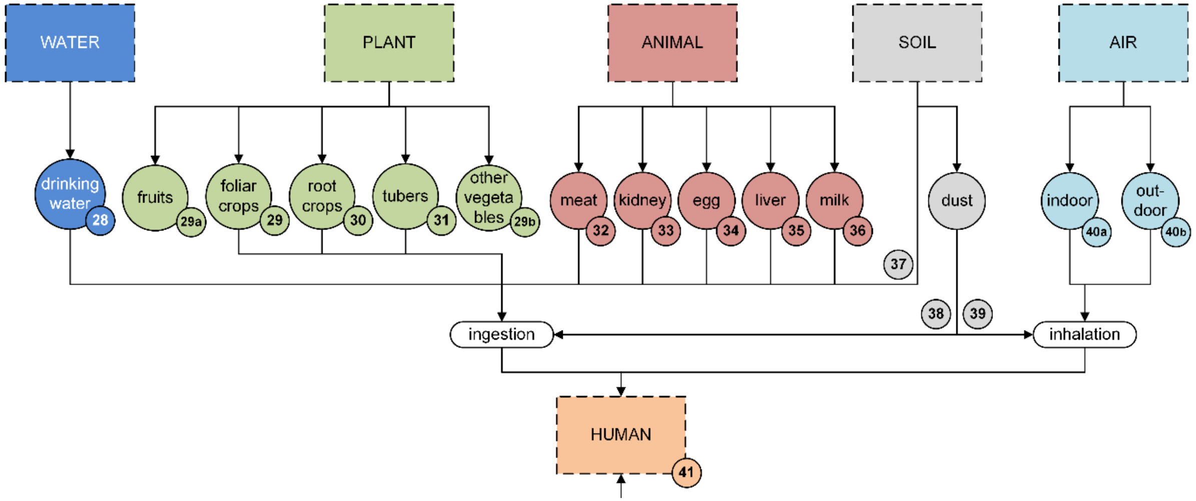


Figure 29. Schematic overview of possible pathways from environmental media to human exposure considered in the source-to-dose models.

Table 53. Overview of the models included in the inventory of existing source-to-dose models, where the considered pathways from environmental media to human exposure are indicated per model. The numbers correspond to the numbers in Figure 29.

	Human exposure routes																			
		Ingestion															Inhalation			
		WATER	PLANT						ANIMAL						SOIL			AIR	
		28	29a	29b	29	30	31	other	32	33	34	35	36	Other	37	38	39	40a	40b
Model	Exposure sources considered for human exposure	Drinking water	Fruits	Other vegetab	Foliar crops	Root crops	Tubers		Meat	Kidney	Egg	Liver	Milk		Soil ingest	Dust ingesti	Dust inhal	Indoor	Outdoor
EUSES +	Drinking water, soil, air, fish, crop, meat, milk	x	x		x	x	x		x				x	Fish	x	x	X	x	
MERLIN-Expo	Surface water, soil, atmosphere, phytoplankton, invertebrates, fish, plant, human	x	x		x	x	x	Fruit + grain	x				x	Fish			x	x	
S-risk	Drinking water, groundwater, soil, dust, air, crop, meat, milk, eggs	x	x		x	x	x		x		x		x		x	x	x	x	x
Cal-Tox	Drinking water, groundwater, soil, dust, air, crop, meat, milk, eggs, fish, seafood	x	x		x	x	x		x		x		x	Fish+sea food	x		x	x	x
CSOIL	Drinking water, soil, dust, air, crop	x	x		x	x	x								x		x	x	X
Cd mass balance	Soil, atmospheric deposition, irrigation water, food, wheat,potato						x	Wheat											
IEUBK	Drinking water, soil, dust, air, food, paint and prenatal (maternal) blood Pb concentrations	x						food							x	x	x	x	
PHAGM	Soil, dust, air														x	x	x	x	
USEtox PFAS	Consumer products, indoor and outdoor air, soil, water	x	x		x	x	x		x				x	Fish					
SMURF	Indoor & outdoor air, urban film, surface water, soil, sediment, vertical & horizontal surfaces (indoor)																		
CLEA	Soil, dust, crops, air		x		x	x	x								x		x	x	x
Atlantic RBCA	Soil, groundwater, air, food							Food										x	
HOUGH	Soil, dust, air, crops, milk, meat		x		x	x	x		x				x		x		x	x	
RISKNET	Air, soil, dust, groundwater														x			x	x
POPs toolkit	Soil, dust, air, water, food	x														x			
RAIS	Soil, air, water, food, fish	x	x		x	x	x								x		x	x	
INTEGRA	Soil, dust, air, water, crops, meat, milk, fish	x	x		x	x	x								x			x	x

Table 54. Additional information on the considered models.

Model	Dynamic (D) vs steady state (SS)	Land use scenarios	Background exposure	Model input	Age group	External/internal PBPK	Chemicals	Deterministic vs probabilistic	Uncertainty or sensitivity analysis	Case studies	Model format	Features lacking
EUSES +	SS	/	Fraction of homegrown vegetables vs commercial	Soil, aerial deposition, air	Toddlers and adults	Both, internal only blood	Pb, modifiable	Deterministic	/	Tiered approach Pb exposure (De Brouwere et al. 2022)	Excel	Chemical database Uncertainty Background exposure Dynamic Probabilities
MERLIN-Expo	Both	/	Calculated externally	Surface water, soil	0-…	Both	Br flame retardants, dioxins, metals (Pb, As), PAHs, PCBs, pesticides, phenols, phthalates, VOCs, modifiable	Both	Both	PFOA and PFOS, Pb, As	Standalone program	No transfer to animal products Background exposure Land use scenarios
S-risk	SS	9 available, modifiable land use scenarios	Automatically calculated, modifiable (food, drinking water & air)	water, soil	10 age groups, from 1 - >61 years	External	Heavy metals, BTEXs, PAHs, chlorinated compounds, PFOS, PFOA, modifiable new parameters can be entered	Deterministic	/	Soil remediation values for chlorinated compounds, PFOS and PFOA	Web app	Dynamic Probabilities No aerial deposition No uncertainty
Cal-Tox	Dynamic	/	/	Water, soil, air	/	External	Non-ionic organic chemicals; inorganic chemicals, ionic organic, radionuclides and metals possible with modifications	Probabilistic	Both	Many	Excel	Not designed or tested for surfactants Hard to use Only when soil is primary source of contamination
CSOIL	Steady state	7, modifiable land use scenarios	/	Soil	Child and adult)	External	metals, inorganic contaminants, organic contaminants, and dissociating organic contaminants.Database included, not modifiable	Deterministic	/	Many	Excel	Chemical database not modifiable No background exposure No uncertainty Dynamic Probabilities
Cd mass balance	Dynamic	/	/	soil, rainwater quantity, agricultural yields, deposition, irrigation water	Child and adult	Both	Cd	Probabilistic	Both	Cd reduction in fertilizers	R scripts	No background exposure (local vs. commercial) No chemical database
IEUBK	Dynamic	/	built-in defaults for USA	food, drinking water, soil, dust, air, paint (alternate) and prenatal (maternal) blood Pb concentrations	6 months - 7 years	Both	Pb, modifiable for external exposure only	Probabilistic**	Sensitivity, only for media concentrations	Slovenia: lead exposure children	Standalone program	Smoothed over 1 year periods
PHAGM	Steady state	/	/	soil, dust, frequency of exposure	Babies, children, children soil pica, pre-adults, adults	External	Hg, Cr, Ni, Cu, Zn, As, Cd, Pb	Deterministic	/	Hg from soil and dust PTE in dust	Equations in papers	Dynamic Probabilities Background exposure Limited exposure routes
USEtox PFAS	Steady state	/	/	?	/	External	PFAS, organic chemicals, metal ions, industrial releases, agricultural emissions	Deterministic	Both	In paper	Excel, freely available	Mainly focused on LCA
SMURF	Steady state	Emission scenarios	Background effect due to advection	?	/	/ (no exposure)	PAHs, formaldehyde, 2,4,6-TBP, DEHP, BDE 209	Deterministic	Sensitivity analysis	Fate of PAHs in Stockholm	Excel	
CLEA	Steady state	Large number, modifiable scenarios	/	soil	Children, adults	External	Dioxins, furans, DL-PCBs, chlorinated compounds, metals, modifiable	Deterministic	/	PAHs, dioxins, furans, heavy metals (Jeffries 2009; Jeffries and Martin 2009)	Excel	Not able to add additional pathway No meat or eggs

Model	Dynamic (D) vs steady state (SS)	Land use scenarios	Background exposure	Model input	Age group	External/internal PBPK	Chemicals	Deterministic vs probabilistic	Uncertainty or sensitivity analysis	Case studies	Model format	Features lacking
Atlantic RBCA	Steady state	4	/	soil	/	External	Petroleum hydrocarbons, CVOCs	Deterministic	/	RBCA evaluations (Atlantic PIRI 2022)	Excel	Limited chemicals $990 32-bit Excel
HOUGH	Steady state	2	?	soil concentration, pH and organic content	Adults	External	Range of inorganic and organic	Probabilistic	/	Pb, As, Cd, Cr in urban gardens (Hough 2022)	Excel?	PhD thesis not freely accessible
RISKNET	Steady state	2	?	soil concentration, land use scenarios, site and soil properties	/	External	Database, modifiable	Deterministic	/	Italy policy documents	Standalone app (Verginelli 2024)	Only risk hazard calculations No food
POPs toolkit	Steady state	6	/	Concentration in soils/drinking water/particles in the air, (accidental) soil/water/food ingestion rate for adult, absorption factor for the gastrointestinal tract/skin, surface area of exposed skin, soil loading to exposed skin, time of exposure, body weight of receptor, life expectancy	Infant, toddler, child, teen, adult	External (provides expressions of HH risk e.g. Hazard Quotients)	POPs	Deterministic	/	Risk assessment POP hot spots in Cambodia, Lao PDR, Malaysia and Thailand	Web app (POPs Toolkit 2025)	Dynamic Probabilities Background exposure Limited exposure routes No uncertainty
RAIS	Steady state	8	Integrated	Soil, sediments, water and air concentration; scenarios for land; site, soil, air properties; physico-chemical distribution constants; intake parameters such as inhalation rate	/	External, (non-)carcinogenic risk	Chemicals	Deterministic	/	/	Website (The Risk Assessment Information System (RAIS) 2025)	Dynamic Probabilities Concentrations No uncertainty
INTEGRA	Both	3	Through food web	Release rate in various environmental media, environmental media concentrations, physicochemical properties, toxicokinetic properties	0-80 years	Both		Probabilistic	Both	BPA	Web app	No eggs No included chemical database

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