UNIVERSITÉ DE MONTRÉAL

INTÉGRATION DES IMPACTS SUR LA SANTÉ DES TRAVAILLEURS DUS AUX EXPOSITIONS PROFESSIONNELLES AUX POLLUANTS À L'ANALYSE DU CYCLE DE VIE

GAËL KIJKO
DÉPARTEMENT DE MATHÉMATIQUES ET DE GÉNIE INDUSTRIEL
ÉCOLE POLYTECHNIQUE DE MONTRÉAL

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Cette thèse intitulée :

INTÉGRATION DES IMPACTS SUR LA SANTÉ DES TRAVAILLEURS DUS AUX EXPOSITIONS PROFESSIONNELLES AUX POLLUANTS À L'ANALYSE DU CYCLE DE VIE

présentée par : KIJKO Gaël

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a été dûment acceptée par le jury d'examen constitué de :

M. SAMSON Réjean, Ph. D., président

M. MARGNI Manuele, Doctorat, membre et directeur de recherche

M. JOLLIET Olivier, Ph. D., membre et codirecteur de recherche

Mme BULLE Cécile, Ph. D., membre

Mme LLOYD Shannon, Ph. D., membre externe

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RÉSUMÉ

La santé humaine est l’un des grands enjeux de l’analyse du cycle de vie (ACV). Les impacts sur la santé humaine prennent en compte principalement l’exposition aux polluants émis dans l’environnement tout au long du cycle de vie du produit. Au cours des dix dernières années, plusieurs travaux de recherche ont montré l’importance des impacts des conditions de travail sur la santé des travailleurs mais les grandes méthodes ACV et les études ACV ne prennent pas cette problématique en compte. Les principales méthodes existantes pour évaluer l’impact sur la santé des travailleurs reposent soit sur l’analyse des statistiques d’accidents et de maladies professionnelles, soit sur des modèles d’exposition aux polluants en milieu de travail. Il n’existe pas de méthode spécifique aux expositions aux polluants en milieu de travail qui repose sur un modèle de cause à effet et qui permette d’avoir une analyse à l’échelle d’un cycle de vie. Cette thèse présente une revue de la littérature existante traitant de l’intégration de la santé et sécurité au travail en ACV. Une méthode est ensuite proposée pour modéliser l’impact potentiel sur les travailleurs d’un secteur industriel lié à l’exposition à l’inhalation de substances chimiques en milieu de travail, en combinant les concentrations d’exposition au temps de travail nécessaire dans ce secteur par unité fonctionnelle. Elle repose sur l’utilisation de données publiques de concentrations de polluants en milieu de travail et sur la chaîne de cause à effet recommandée en ACV via l’utilisation des facteurs d’effet de USEtox. Les facteurs de caractérisation (FC) pour l’ensemble des secteurs industriels de l’économie des États-Unis sont fournis avec des intervalles de confiance, permettant ainsi de calculer un impact potentiel de l’exposition des travailleurs aux polluants organiques par heure travaillée. Une seconde méthode est ensuite présentée, permettant d’étendre l’utilisation des FC fournis par la première méthode à l’échelle d’une chaîne de valeur via l’utilisation d’un modèle économique input output. Les FC permettant de calculer l’impact potentiel sur les travailleurs de l’exposition aux polluants organiques sur l’ensemble de la chaîne de valeur sont fournis par dollar de production de chaque secteur de l’économie. Finalement, des FC mis à jour sont fournis afin de prendre en compte les données les plus récentes ainsi que les polluants inorganiques et matières particulaires.

ABSTRACT

Human health is one of the main foci of life cycle assessment (LCA). Impacts on human health are primarily modelled based on outdoor emissions of pollutants from all life cycle stages and subsequent human exposure. In the past decade, various scientific publications have pointed out the importance of including work environment in LCA but this has not yet lead to a formal inclusion. Existing methods focusing on work environments in an LCA are built upon either occupational injury and illnesses statistics or occupational chemical exposures models. This thesis addresses the need for a method that simultaneously makes use of a cause to effect model for chemical exposure and provides a life cycle perspective.

The thesis includes a literature review focusing on LCA and the working environment. A method is then developed with a focus on occupational exposure to organic chemicals. This method relies upon a measured occupational chemical concentration database; it models the potential impacts combining the concentrations with effect factors from the USEtox model and the number of hours of work per functional unit. Characterization factors (CF) are provided for all manufacturing sectors of the United States economy with confidence intervals. The CFs correspond to potential impact per hour worked in each industrial sector of the economy. A second method is proposed, extending the first method to model entire value chains through the use of an input output economic model. Corresponding CF represent the potential impact on worker health of occupational exposures to organic chemicals by inhalation in the entire value chain per dollar of value of an economic sector output. Finally, the CF are updated using the most up-to date data and expanded to also assess inorganic chemicals and particulate matter.

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LISTE DES SIGLES ET ABRÉVIATIONS

ACV	Analyse du Cycle de Vie
ACGIH	association américaine pour la promotion de la santé au travail et de l'environnement
AICV	Analyse des Impacts du Cycle de Vie
ASM	Annual Survey of Manufacture
BEA	Bureau of Economic Analysis
BCWH	Blue Collar Worker Hour
CF	Characterization Factor
CEHD	Chemical Exposure Health Data
DALY	Disability Adjusted Life Years
DTU	Université Technologique du Danemark
ECHA	l'agence européenne des produits chimiques
EF	Effect Factor
EPA	Environmental Protection Agency
ETID	Exposure to Impact Delay
É-U	États Unis
FC	Facteur de Caractérisation
FE	Facteur d'Effet
FU	Functional Unit
GBD	Global Burden of Disease
HH	Human Health
IARC	International Agency for Research on Cancer
IDLH	Immediately Dangerous for Life and Health

ILO	International Labour Organization
IMIS	the Integrated Management Information System
I-O	Input-Output
ILO	International Labour Organization
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
LEP	Limite d’Éxposition Professionnelle
NAICS	North American Industry Classification System
NHANES	National Health and Nutrition Examination Survey
OHS	Occupational Health and Safety
OLV	Occupational Limit Value
OSHA	Occupational Safety and Health Administration
REACH	Enregistrement, évaluation, autorisation et restriction des substances chimiques
SETAC	Society for Environmental Toxicology and Chemistry
SF	Severity Factor
TBD	Total Burden of Disease
US	United States
VOC	Volatil Organic Compound
WE-DALY	Work Environment – Disability Adjusted Life Years
WE-LCA	Work Environment – Life Cycle Assessment

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CHAPITRE 1: INTRODUCTION

1.1 Mise en contexte

Nous vivons dans une société caractérisée par l'extrême rapidité à laquelle les informations circulent. Et autant cette diffusion est rapide, autant elle nous confronte à des problématiques qui dépassent notre cadre de vie habituel. Nous somme ainsi informés de tout évènement important (catastrophe naturelle, guerre, attentat…) aussi bien, voire mieux, que des actualités de notre localité ou région. C'est le cas pour les changements climatiques avec une mobilisation mondiale de la population, mais c'est aussi le cas pour les disparitions d'espèces, la problématique de la production (et répartition) alimentaire, les manques d'accès à l'eau potable, l'accroissement des inégalités. C'est aussi le cas pour les conditions de travail à travers le monde.

En effet, nous évoluons dans une économie mondialisée, avec des activités industrielles reposant sur des échanges globaux de produits où nous, les consommateurs, sommes maintenant confrontés aux conséquences de nos choix de consommation à travers les médias et les réseaux sociaux. En 2012, un fournisseur d'Apple, Foxconn, a reconnu avoir eu recours à des travailleurs de 14 ans. Le 24 Avril 2013, au Bengladesh, un bâtiment abritant des ateliers de production de vêtements s'est effondré, tuant plus de 1100 travailleurs et en blessant plus de 2000. Cette catastrophe a mis en avant le fait que de nombreuses compagnies textiles faisaient appel à des sous-traitants dans des conditions de travail dangereuses.

La conscientisation des consommateurs par la couverture médiatique de ces évènements entraîne une volonté de responsabilisation des entreprises vis-à-vis de leur chaîne de valeur. Mais pour pouvoir s'informer et prendre des décisions reposant sur les impacts des conditions de travails à travers les chaînes de valeurs des produits il faut d'abord avoir un moyen de les évaluer. Le projet de recherche présenté dans cette thèse porte sur le développement d'un outil d'évaluation des impacts sur la santé des travailleurs des expositions professionnelles aux substances chimiques par inhalation tout au long des chaînes de valeurs.

1.2 La santé et sécurité en milieu de travail

Les notions contemporaines de protections du travailleur et de contrôle des conditions de travail ont commencées à prendre de l'importance entre 1850 et 1900 durant la révolution industrielle. Au Royaume Unis le *Factory Act* a été mis en application en 1833 et comprenait, entre autres, la mise en place d'un âge minimal pour travailler (9 ans), des limites sur le temps de travail quotidien et la création de 4 postes d'inspecteurs chargés de la vérification du respect de la loi (United Kingdom Parliament, 2016). L'encadrement des conditions de travail a beaucoup évolué depuis : dans la plupart des pays un pan important du corpus législatif y est dédié et des organismes publics sont en charge des contrôles réglementaires des lieux de travail (CSST au Canada, OSHA aux États-Unis et l'inspection du travail en France. De plus des organismes ont pour mandat de développer des projets de recherche en santé et sécurité : l'IRSST au Canada, NIOSH aux États Unis, l'INRS en France (Hughes & Ferrett, 2011).

L'analyse des risques est une méthode très utilisée pour évaluer les impacts sur la population et l'environnement. C'est une méthode de type *bottom-up* déterministe permettant l'évaluation de l'exposition et des impacts d'une population dans un contexte local voire régional (Suter & Barnthouse, 2007). Elle s'appuie sur une modélisation fine pour obtenir et a pour but la protection de la population. Dans le domaine SST, elle est utilisée pour évaluer l'impact des conditions de travail sur la santé des travailleurs ainsi que l'acceptabilité de l'exposition à certains dangers dans des situations précises. La grande force de cette méthode est la précision du modèle utilisé, que ce soit pour l'exposition à des polluants volatiles ou pour l'opération de machinerie présentant des dangers. Mais cette précision induit un besoin important en données ce qui est incompatible avec une analyse à l'échelle d'une chaîne de valeur.

1.3 L'ACV

L'ACV est un outil d'aide à la décision permettant de comparer les impacts potentiels de produits ou services sur l'environnement (incluant entre autres les ressources minérales, la santé des écosystèmes, la santé humaine) dans une vision globale du cycle de vie : depuis le berceau (extraction des matières premières) au tombeau (fin de vie du produit) en passant par la production, l'utilisation, les transports et toute étape importante dans le cycle de vie du produit

(European Commission Institute for Environment and Sustainability - Joint Research Center, 2010b; Jolliet, Saadé, & Crettaz, 2005). Le but principal de l'ACV est d'éviter le déplacement d'impacts vers un autre problème environnemental ou vers d'autres étapes du cycle de vie du produit en voulant améliorer une phase spécifique. La norme ISO 14040 indique clairement que l'ACV ne manipule que des *impacts potentiels* du fait de l'utilisation d'unités de références pour les exprimer, du fait de l'intégration de données dans le temps et dans l'espace, du fait de l'incertitude inhérente aux modèles utilisés et du fait que certains impacts potentiels sont censés avoir lieu dans le futur (International Organization for Standardization, 2006).

C'est une approche de type *top-down* qui permet de comparer les impacts potentiels des émissions (resp. prélèvements) vers (resp. depuis) l'environnement à l'échelle d'un cycle de vie. Elle se base sur des données précises pour les processus centraux au cycle de vie et utilise ensuite des données génériques pour représenter le reste des processus pour lesquels aucune information n'est disponible (les chaînes de valeur en particulier) et impacts dus aux chaînes de valeurs en utilisant des données précises pour les génériques tout en laissant la possibilité de préciser des données pour des étapes cruciales. Bien qu'elle soit très différente de l'analyse des risques (*top-down* vs. *bottom-up*, comparative vs déterministe, globale/régionale vs régionale/locale) l'ACV peut être utilisée conjointement à l'analyse des risques (Bare, 2006; Cowell, Fairman, & Lofstedt, 2002; Humbert et al., 2011; Matthews, Lave, & MacLean, 2002; Olsen et al., 2001; Sleeswijk, Heijungs, & Erler, 2003).

Historiquement l'utilisation de l'ACV adresse les impacts des émissions à l'environnement et des extractions de ressources de l'environnement à travers la chaine de valeurs. Peu de travaux de recherche se sont penchés sur l'évaluation des impacts sur la santé des travailleurs tout au long de la même chaîne de valeurs et souvent sont limités à une étude de cas ou un nombre réduit de substances (Antonsson & Carlsson, 1995; Demou, Hellweg, Wilson, Hammond, & McKone, 2009; Hellweg et al., 2009; Scanlon, Lloyd, Gray, Francis, & LaPuma, 2014). L'absence de méthode opérationnelle pour évaluer les impacts sur la santé des travailleurs de l'ensemble des activités impliqués dans une chaine de valeur fait que ceux-ci ne sont actuellement pas pris en compte dans l'état de la pratique en ACV.

CHAPITRE 2: REVUE CRITIQUE DE LA LITTÉRATURE : ARTICLE 1 : WORK ENVIRONMENT IMPACTS ON WORKERS' HEALTH IN LCA: ASSEMBLING THE PIECES

2.1 Présentation de l'article

Ce chapitre présente une revue de la littérature scientifique portant sur la prise en compte des impacts sur la santé des travailleurs en ACV. Il a été rédigé à la fin du projet de recherche et inclus donc les articles publiés dans le cadre de ce projet de recherche. Il comporte aussi une proposition de cadre méthodologique pour l'intégration de l'ensemble des impacts potentiels sur la santé des travailleurs

Auteurs : Gaël Kijko, Scanlon Kelly, Henderson D. Andrew, Manuele Margni.

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2.2 Manuscrit

2.2.1 Introduction

Globally, occupational impacts are ranked 12th out of 17 for impacts to human health, with some variation among countries (10th place for the USA, 9th for the European Union, 8th for Canada, China and Brazil) (Institute for Health Metrics and Evaluation, 2016). Occupational impacts rank slightly lower than human health impacts attributable to unsafe sex or to high total cholesterol. Note that these rankings refer to global health impact to society in general. Occupational impacts are twice more important within the labor force, because active workers are approximately half of the entire population (according to the World Bank definition) and therefore not exposed to occupational risk factors (The World Bank, 2017).

Figure 2.1 presents the main causes of impacts on human health attributable to the work environment in 2015, as published in the 2015 Global Burden of Disease (GBD) (Institute for Health Metrics and Evaluation, 2016). In that year, the work environment was responsible for $1x10^6$ premature deaths, corresponding to $6.4x10^7$ Disability-Adjusted Life Years (DALY, life years with less than ideal health, considering injuries, illnesses and fatalities). Ergonomic stressors, work-related injuries, and exposure to noise are the top three risk factors identified by the GBD study (Institute for Health Metrics and Evaluation, 2016) corresponding to 29%, 21% and 17% of the global impact, respectively. But the three next risk factors - carcinogens, particulates and asthmagens, which are mainly linked to airborne contaminants - sum up to more than 20 million DALYs, or 33% of the total occupational impacts, which ranks first when compared to the other causes.

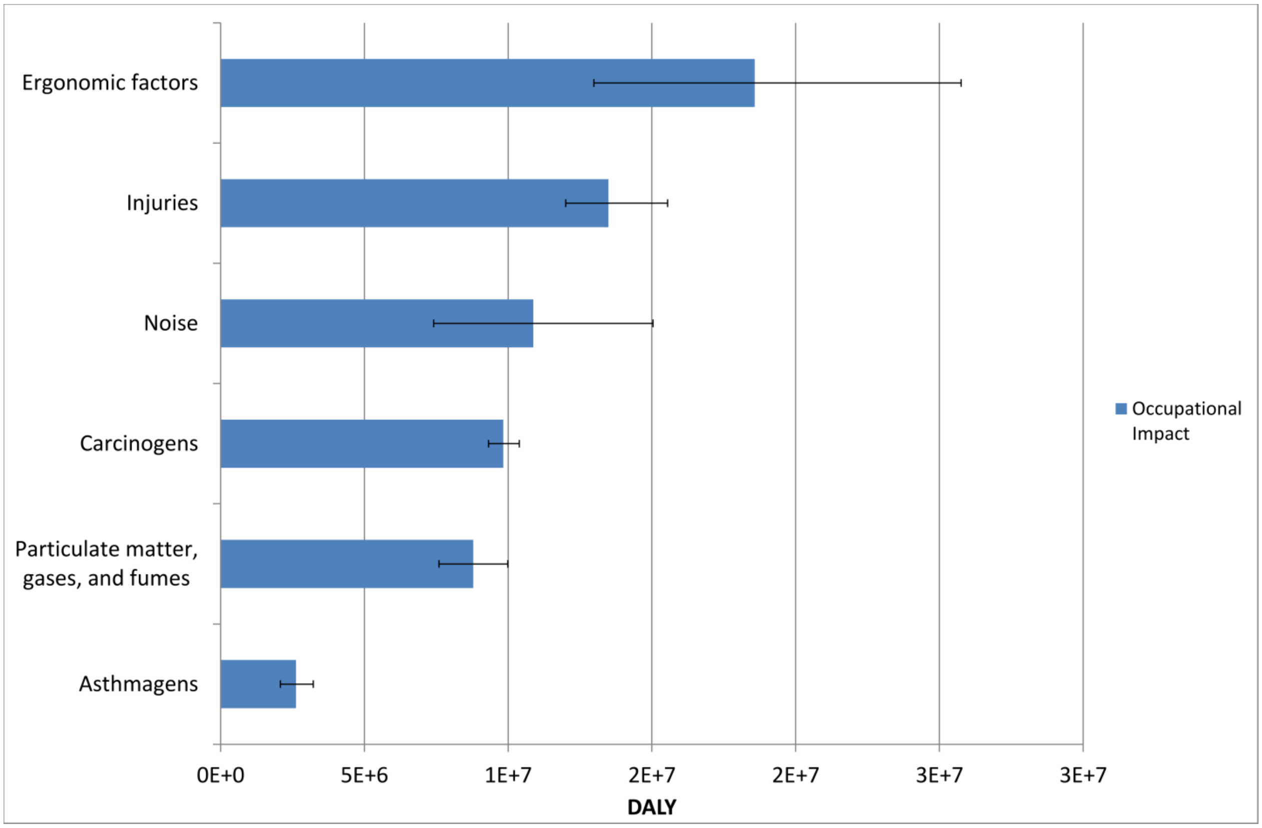

Figure 2.1: Main occupational causes of impact on worker health, based on the global burden of disease (GBD) study (Institute for Health Metrics and Evaluation, 2016) with 95th percent interval confidence

For almost 200 years, occupational health and safety (OHS) has been a growing focus for governments: from the United Kingdom *Factory Act* of 1833 that regulated child labor and created four positions of factory inspectors tasked with law enforcement (United Kingdom Parliament, 2016) to the introduction of the *Prevention of Occupational Disease Law* (2001) and the *Work Safety Law* (2002) in China (Wang et al., 2011). Governments and public agencies have been channeling governmental efforts on OHS for almost 200 years. Examples of such agencies are the national OHS public agencies and organizations (United States: NIOSH, OSHA; France: INRS), the United Nations International Labour Organization (ILO), the British Standards Institution through the standard OHSAS 18001, and also the International Organization for Standardization through its developing ISO 45001 standard. Together, these national and international organizations have published guidance, recommendations and standards relative to OHS and enforced national regulations. This has led to a large drop in the fatal workplace injuries statistics (United Kingdom: 2.9 per 10^6 workers in 1974 to 0.56 per 10^6 workers in 2015 (Health and Safety Executive, 2016), US: 7.38 per 100.000 workers in 1980 to 3.3 in 2014 (Bureau of Labor Statistics, 2016; Department of Health and Human Services, 2004)), but the statistics on occupational illnesses show a different trend: from 20 cases per 10^4 workers in 1984 to 40 cases per 10^4 workers in 2001 for the U.S. These figures, combined with the global burden of occupational impacts show that despite the existing efforts, there is still improvement needed, in particular for illnesses attributed to the work environment.

Regulations and standards evolve along the knowledge of hazards and the social acceptance of the related impacts. For instance, the latest version of ISO 14001 on environmental management (2015) calls for the adoption of a life cycle perspective to identify all environmental aspects that an organization can either control of influence (International Organization for Standardization, 2015). Organizations are therefore encouraged to consider their supply chain, with Life Cycle Assessment being a tool designed for this purpose. LCA is a comparative tool designed to support decision makers by providing indicators on environmental, human health, social and economic impacts of products or services across their life cycles, from raw material extraction through disposal (Jolliet et al., 2005). LCA can be used to assess various impact pathways to human health, like those reported in the GBD.

The European commission is developing an LCA based labeling scheme to inform consumers on the environmental performance of retail products. Further initiatives involving the private sector, such as the Sustainable Apparel Coalition, aims to provide retailers and manufacturers tools to enhance life cycle product stewardship. In the U.S., the Safer Choice program at the Environmental Protection Agency (EPA) has conducted studies exploring the life cycle impact of different items (wire and cables insulation, solders in electronics), including an analysis of the toxicity of workplace chemicals (Geibig & Socolof, 2005; Socolof, Overly, Kincaid, & Geibig, 2001; Socolof, Smith, Cooper, & Amarakoon, 2008). None of these initiatives includes comprehensive impacts on worker health, however they show that a global concern can lead to a change in regulation and standards. However, concern about worker health has not yet led to life-cycle thinking being included in OHS standard or regulation.

Environmental LCA (eLCA), as per ISO 14040 “considers all attributes or aspects of natural environment, human health and resources” (International Organization for Standardization, 2006). Despite the goal of comprehensiveness of LCA, which is necessary to identify potential trade-offs, work environment impacts on worker health are yet to be fully included (Bare & Gloria, 2008). Occupational Health and Safety (OHS) aspects can be covered by both eLCA and social LCA (sLCA) with overlapping risks (Andrews et al., 2009).

Impacts on human health in LCA are expressed in number of cases of diseases, classified as cancer or non-cancer units (Crettaz, Pennington, Rhomberg, Brand, & Jolliet, 2002; Pennington et al., 2002) or DALYs (Huijbregts, Rombouts, Ragas, & van de Meent, 2005; Murray, C. J., 1994). Number of cases are considered a mid-point indicator: it characterizes the problem, allowing intermediate summation across various hazards, while the DALYs are endpoint indicators describing the damages and allowing a further summation across various sources of impacts on human health (Frischknecht et al., 2016; Jolliet et al., 2014; UNEP / SETAC Life Cycle Initiative, 2016). In LCA, each emission is seen as a marginal increase over ceteris paribus situation. The impact assessment is therefore calculated as marginal increase of an accumulated impact over time and space under the hypothesis that toxicological phenomena are linear (Crettaz et al., 2002; McKone, Kyle, Jolliet, Irving Olsen, & Hauschild, 2006; Pennington et al., 2002). This means that the toxicological effect is modelled being directly proportional to the chemical exposure, and by extension, the damage is directly proportional to the emission (through a factor called characterization factor, or CF). While this hypothesis is not consistent with the modeling of threshold based toxicological effects, it has the advantage of assessing a chemical exposure independently of the situation of the background system. For instance, the potential impact of inhaling 1g of a chemical is the same regardless if one is already exposed or not to this chemical. In an occupational setting, this makes it possible to compare exposure of workers even if they are exposed differently to chemicals outside of work. Synergetic actions of chemicals on human health are not modeled in LCA.

Different articles point out that all occupational risk factors (element or characteristic of the occupational environment that may harm worker exposed to it) should be included in eLCA and that using these methodologies to assess impacts will be a choice left to practitioners depending on the goal and scope of the study (European Commission Institute for Environment and Sustainability - Joint Research Center, 2010a; Hofstetter & Norris, 2003; Pettersen & Hertwich, 2008; Schmidt, A., Poulsen, Andreasen, Fløe, & Poulsen, 2004). An effort to identify existing methods and provide guidance for the development of the Work Environment LCA (WE-LCA) was started by the United Nation Environment Program - Society for Environmental Toxicology and Chemistry (SETAC) Working Group on LCA and the Working Environment in 1998 that led to the publication of a report by Poulsen et Jensen (2004). The UNEP-SETAC have partnered in 2002 to launch the Life Cycle Initiative that helps coordinate the research effort, identify good practices and promote life cycle thinking (UNEP-SETAC Life Cycle Initiative, 2017).

Figure 2.1 presents, in the upper part, a diagram illustrating the generic cause-to-effect framework for occupational health, based on the cause-to effect framework from Jolliet et al. (2003). As an example, the bottom part of Figure 2.1 present the same cause-to-effect framework used in Life Cycle Impact Assessment (LCIA) for the chemical hazard of a volatile chemical. Impacts on worker health result from exposure to work environment hazards (left side of Figure 2.2) such as the presence of toxic chemicals. The types of hazards depend on the work environment characteristics. Hazards are potential sources of damage to health that, upon exposure, may result in adverse physical or psychological effects. Exposure is classified based on duration, frequency, intensity, and route, for example, inhalation, ingestion, or dermal exposure. A risk is then characterized by modeling the effect on human health as a function of individual characteristics, such as hardiness to physical recovery capacity or sensitivity to chemicals. LCIA tends to model long term impacts due to chronic exposures, but in occupational environment, short term impact due to acute exposure are responsible for a large part of impacts on worker health. Thus it is important to consider the exposure to impact delay (ETID), which corresponds to the time lapse between the exposure to a hazard and the adverse effect or impact on worker health. A short ETID is one where the exposure results in immediate injury, illness, or fatality, like a slip, a trip, a fall accident, or an acute exposure to chemicals. A long ETID is one where the exposure results in an injury, illness, or fatality in the future, like low dose exposure to a carcinogen or teratogen.

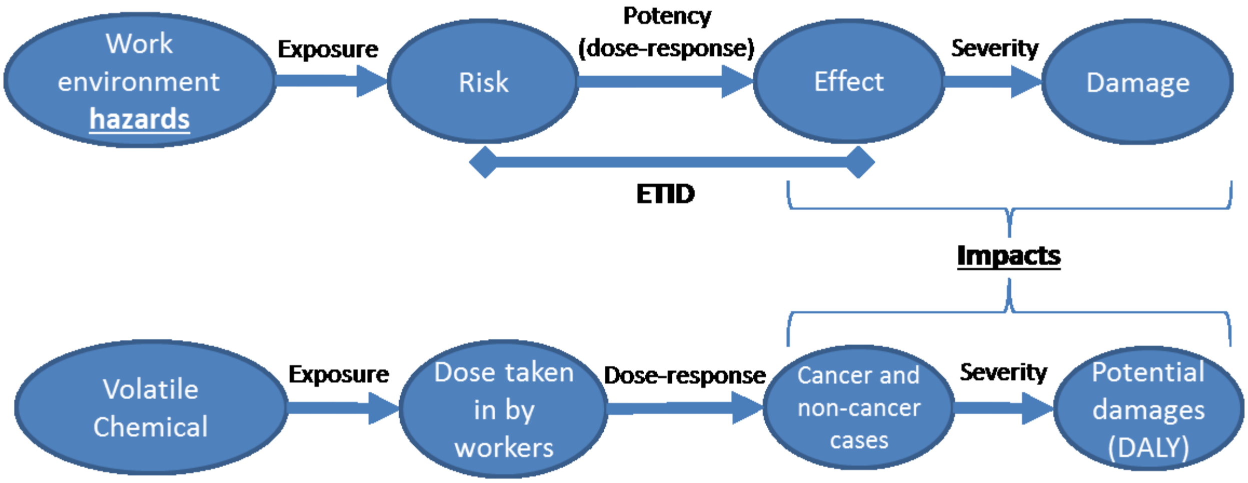

Figure 2.2: Generic Occupational health impact cause-to-effect general framework, adapted from Jolliet et al. (2003) (top), and volatile chemical hazard specific cause-to-effect framework as example (bottom)

Figure 2.3 presents the two main approaches to classify hazards and impacts used in OHS. Figure 2.3 a) presents one version of the hazard classification (Hughes & Ferrett, 2011; Smedley, Dick, & Sadhra, 2013), but many variations exist (e.g., in some, the radiological hazards are not under the physical category, but a category on their own). Several OHS agencies also use this hazard classification such as the Australian Comcare (Australian Government - Comcare, 2016) and the Canadian Center for Occupational Health and Safety (Canadian Center for Occupational Health and Safety (CCOHS), 2016). This classification is widely used for hazard prevention activities. Figure 2.3 b) presents one version of an impact classification: the Occupational Injury and Illness Classification System (OIICS v2.01) as developed by the US Bureau of Labor Statistics (Barnett et al., 2012). This classification is oriented toward the reporting of injury and illness and is commonly used in the reporting of OHS statistics. Other variations of this classification exist.

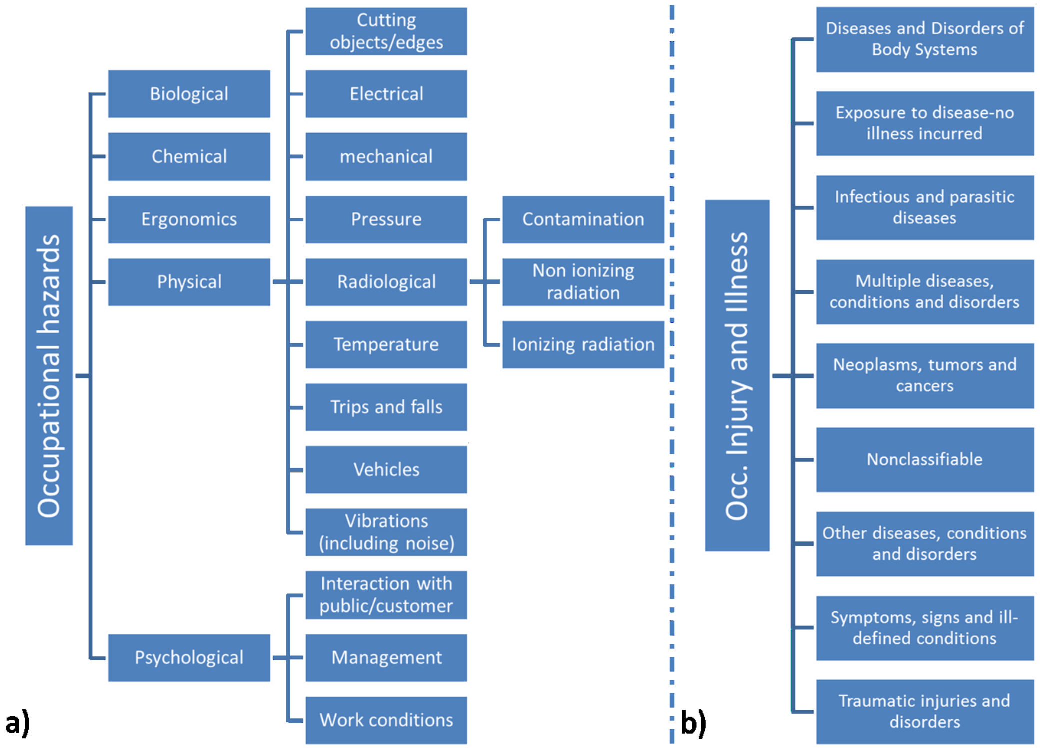

Figure 2.3 : two main classifications used in OHS a) Hazard classification, b) Effect (Occupational Injury and Illness) Classification System

The purpose of this paper is to define and to promote an approach for the inclusion of OHS in LCIA. To that end, the specific objectives are (a) to provide a literature review of research work integrating OHS in LCIA, (b) to define a set of criteria defining an ideal method able to capture occupational exposure to hazards or risks and damages to worker health in LCIA, (c) analyze the identified methods based on the criteria and (d) provide the outline of a framework to incorporate identified methods to an LCIA context.

2.2.2 Methods

2.2.2.1 Literature review

To perform a review of existing literature, the following research strategy was developed: we first used online scientific search engines such as Web of Science to identify English language documents covering both Life-Cycle Assessment and Occupational Health and Safety. The following query was used : ((occupational or "work environment" or "working environment" or

"OHS" or "EHS") and ("LCA" or "life cycle assessment" or "life-cycle assessment" or "life cycle analysis" or "life-cycle analysis" or "life cycle impact" or "life-cycle impact" or "LCIA")). The bibliographies of the identified research articles were also screened for additional publications. Only publications referring to LCIA and considering the inclusion of part or all of OHS impacts on workers into LCA were kept. We also kept articles considering LCIA and the "indoor environment" when it was defined as including occupational settings.

Each document was then categorized as one or more of the following: review, guidance documents, methods and case study. Reviews are documents, such as the present article, that aims at providing a snapshot of the state of research for a given subject at a given time. Guidance documents include both guidelines and frameworks, derived from theoretical or taxonomic approaches, upon which methods can be developed. Methods provide quantified metrics and indicators, beyond general principles. Case studies are applications of those tools to specific situations. Case studies are specific examples of method use.

2.2.2.2 Defining selection criteria

An ideal method aiming to include OHS in LCIA would capture, separately, all risks or occupational exposures to hazards, and by extension, all impact on worker health. Human health impact indicators would be expressed or converted into common LCIA units (cases of diseases, DALY). The LCIA characterization method would build upon work environment characteristics, model worker exposure and integrate dose-response function to assess human health impact. An ideal method would provide default CFs at an elementary flow level linked to existing datasets from LCA databases and allow to overwrite default data with measured site-specific for a better representativeness.

Building upon the definition of the ideal method, a set of five criteria is defined to analyze existing methods. The two first criteria are the type of hazard and the impacts covered, respectively. Methods should cover all the hazards and impacts described above. A third criterion analyzes the covered steps of the cause-to-effect chain (as per Figure 2.2). The fourth criterion is the provision of CFs with the method and the fifth is relative to the resolution of the method: do the CF representing countries, industrial sectors, companies, or activities? The last criterion is the existence of a link to a life cycle perspective: have the authors provided a way to cover a whole lifecycle with the method? This link can be through the use of an Input-Output model or the mapping to an LCA database. An input output model is a tool based on the economic sectors interdependencies that enables the modeling of value chains (Leontief, 1986; Suh, S., Society for Environmental Toxicology and Chemistry, & International Society for Industrial Ecology, 2009).

2.2.2.3 Comparing the identified methods

The identified methods are analyzed against the above criteria aiming to provide the outline of a framework to incorporate identified methods to an LCA context and then identify opportunities for researchers and users. Identifying weakness in the actual coverage of hazards and effects would help promote the development of methods to strengthen this coverage.

2.2.3 Results

2.2.3.1 Literature Review

The identification of pertinent literature led to 83 results, including 65 articles, published from 1995 to 2017. We only analyzed 36 publications of the 83 that cover both LCA and OHS, i.e. 26 articles, 8 reports, a thesis and a book chapter. They include 11 case studies, 19 methods (eight including a case study) and six guidance documents. Most of the literature (92%) was published after 2000, with only three documents published before 2004. Several key dates can help explain the time pattern of publications: in 2004, the SETAC Working Group on LCA and the Working Environment published its first report. In 2009, a working group under the UNEP/SETAC Life Cycle initiative published an article summarizing its work on the inclusion of indoor exposure to chemicals in LCA (Hellweg et al., 2009). The same year, the guidelines for sLCA of products were also published (Andrews et al., 2009). A timeline of the publications is presented in supporting information (see Figure A.1 in Annex A).

84% of the publications are relative to eLCA with six of the identified publication specific to sLCA. Most published methods include a case study, explaining the similar figure for both. Among the six guidance documents, three are specific to sLCA and include parts specific to EHS, two are focused on the use of nanoparticles in indoor environment (including occupational) and one is a thesis providing a review of existing methods to include OHS in LCA.

Among the 20 identified case studies (eight being published with a method), 14 are *hazard-based*, five are *impact-based* and one can be considered as both. Thirteen case studies are specific to chemical hazard by inhalation with 10 of them focusing on a single activity (eight for degreasing). Only one provides both a life-cycle perspective and full coverage of the cause-to-effect chain. Seven of the 10 activity specific case studies only focus on one or two chemicals. Details on the case studies are available in supporting information (see table A.1 in Annex A).

2.2.3.2 Methods analysis

The 19 identified methods can be grouped into two categories:

- *impact-based* methods, methods modelling the impacts on human health from statistical data such as occupational injuries and illnesses.
- *hazard-based* methods, methods modelling exposure to hazards (relying on data such as emitted quantity or concentration of harmful chemical, noise level) and then characterize those exposure into impacts to human health;

Eleven of the 19 identified methods are *hazard-based*, seven are *impact-based* and one can be classified in both categories.

2.2.3.2.1 Impact-based *methods*

These methods are *impact oriented* as they focus on the impact side of the OHS framework (see Figure 2.2). They model potential impact on worker health based on historical fatal and nonfatal injury and illness data, bypassing the modeling of cause-to-effect. The first method exploring the possibility of using injury and illness statistics to account for OHS in LCA is the oldest article found in the literature review: Antonsson et Carlsson (1995) calculated characterization factors for Swedish industries. This first method offers quantitative and qualitative (for carcinogenic impact and impact on reproduction) ways to evaluate the occupational impacts on worker health. Hofstetter et Norris (2003) identified input-output (I-O) analysis as a suitable tool to account for occupational impacts occurring in the supply chain. They provided CFs for 491 sectors, based on sector specific statistics, but relied on an I-O model of the U.S. economy with 91 sectors to model the supply chain. Schmidt, A. et al. (2004) published a similar method that, instead of relying on an I-O economic model, calculates working environment CFs for 80 sectors of the US economy and maps them to commodities in the LCA database (in term of injury or disease per physical quantity of commodity). Similar methods were published by Hendrickson, Lave et Matthews (2006), but using an IO model of the US economy with 80 sectors then aggregated to only 38 industrial sectors, and by Kim et Hur (2009), using an I-O model of the Korean economy with only 28 sectors specific to the Korean economy. More recently, Scanlon *et al.* published two articles defining work environment disability adjusted life years (WE-DALY) (Murray, C. J., 1994) and providing CFs for 127 U.S. industries covering work related activities in a proof of concept LCA method (Scanlon, Gray, Francis, Lloyd, & LaPuma, 2013; Scanlon et al., 2014).

Impact-based methods can cover, in theory, all hazard type and all damage type. They can also be linked to a life cycle perspective through the mapping of the CF to an LCA database or through the use of an I-O model. On the seven *impact-based* methods identified, six calculate damages consistently with LCIA practices and also model the value chain thus providing a way to address the life cycle perspective. All six provide part or all CF needed to include them in an LCIA analysis.

2.2.3.2.2 Hazard-based *methods*

Hazard-based methods are *cause oriented*; they focus on the hazard side of the OHS taxonomy (see Figure 2.2). All the *hazard-based* existing methods are hazard specific (even route of exposure specific) and capture only long-term impacts thus excluding short ETID, like many documented workplace injuries or fatalities. Among all occupational hazards, chemical hazards offer the most publicly available data for researchers to work with, mostly for exposure by inhalation. It is then not surprising that eight out of 12 *hazard-based* methods identified in this review are specific to potential damage through exposure to chemicals by inhalation. Exposure modeling is used to estimate intake of a chemical, *hazard-based* methods specific to chemical exposure only deal with inhalation route of exposure. Effect modeling is used to estimate the potential consequences of the exposure to the worker health based on the hypothesis of a linear dose-response curve (Crettaz et al., 2002; McKone et al., 2006; Pennington et al., 2002). Finally, impact modeling links the number of cases of illness to DALY through a severity factor (i.e. converting a potential impact expressed in cases into DALY units) based on the GBD study

(Huijbregts et al., 2005). Of these eight methods, only three provide a damage assessment, and three provide a link to a life cycle perspective. This means that the other *hazard-based* methods specific to chemical exposure by inhalation that have been developed for LCIA are either not compatible with the LCIA recommended practices for human health or are missing a critical link with the life cycle perspective. Two methods for noise developed by Cucurachi, Heijungs et Ohlau (2012) and Cucurachi et Heijungs (2014) provide CFs for Europe, but the underlying characterization model miss the link from noise exposure to effect and damage on human health. One other method specifically address psychological impacts but only considers potential exposure of workers to harmful work conditions (through the use of work hours at risk unit) and does not link these exposure to potential damages (Benoit-Norris, Cavan, & Norris, 2012).

Of the 11 *hazard-based* methods identified, none provides CF at the elementary flow level, although one, Kijko, G., Jolliet et Margni (2016), provides CFs for impacts that include the value chain, making it possible to address the life-cycle perspective consistently with LCIA.

Hosseinijou, Mansour et Shirazi (2014) is the only method corresponding to both *impact-based* and *hazard-based* categories. It builds upon Benoit-Norris et al. (2012), which is a *hazard-based* method and adds to it the use of OHS statistics specific to the case studied. This addition is *damage-based*, and while this enables the practitioner to make the best use of available data it does provide neither a life cycle perspective nor a damage assessment. Also, the indicators of both part of the method are distinct preventing from comparing them. The Hosseinijou et al. (2014) reference can in fact be considered as a publication of two different methods.

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Tableau 2-1 Detail of identified methods, blue lines are *impact-based* methods, white line are *hazard-based* methods, purple are methods that are both *hazard-based* and *impact-based*, HRED corresponds to the 4 steps in the cause-to-effect chain (H: Hazard, R: Risk, E: Effect, D: Damage) with grey cell being the steps not included. ETID stands for Exposure to Impact Delay

Authors	**Paper title**	**Hazards covered**	**Damage covered**	**Covered steps of the cause-to-effect chain**				**CF availability**	**CF resolution**	**Link to Life Cycle**
Antonsson et Carlsson (1995)	The basis for a method to integrate work environment in life cycle assessments	All for which data are available	All for which data are available, short and long ETID	H	R	E	D	+ / -	Process / product	Mapping to LCA inventory
Hofstetter et Norris (2003)	Why and how should we assess occupational health impacts in integrated product policy?	All for which data are available	All for which data are available, short and long ETID	H	R	E	D	+	Economic sector	I-O model
Schmidt, A. et al. (2004)	LCA and the working environment	All for which data are available	All for which data are available, short and long ETID	H	R	E	D	+	Economic sector	Mapping to LCA inventory
Hellweg, Demou, Scheringer, McKone et Hungerbühler (2005)	Confronting workplace exposure to chemicals with LCA: examples of trichloroethylene and perchloroethylene in metal degreasing and dry cleaning	Chemical (inhalation)	no impact assessment	H	R	E	D	-	Process / Activity	None
Hendrickson et al. (2006)	Environmental life cycle assessment of goods and services: an input-output approach. (Chapter 15: Occupational safety risks in an input-output framework)	All for which data are available	All for which data are available, short and long ETID	H	R	E	D	+	Economic sector	I-O model
Kim et Hur (2009)	Integration of working environment into life cycle assessment framework	All for which data are available	no damage assessment (considers Lost Work Days)	H	R	E	D	+	Economic sector	I-O model
Hellweg et al. (2009)	Integrating Human Indoor Air Pollutant Exposure within Life Cycle Assessment	Chemical (inhalation)	no impact assessment	H	R	E	D	-	Process / Activity	None
Demou et al. (2009)	Evaluating indoor exposure modeling alternatives for LCA: a case study in the vehicle repair industry	Chemical (inhalation)	no impact assessment	H	R	E	D	-	Process / Activity	None
Cucurachi et al. (2012)	Towards a general framework for including noise impacts in LCA	Noise	no impact assessment	H	R	E	D	-	na	None
Benoit-Norris et al. (2012)	Identifying Social Impacts in Product Supply Chains: Overview and Application of the Social Hotspot Database	Psychological	no impact assessment	H	R	E	D	+	Sector / Country	I-O model
Scanlon et al. (2013)	The work environment disability-adjusted life	All for which data are available	All for which data are available, short and long ETID	H	R	E	D	+ / -	Industry	Mapping to LCA inventory

Table 2 1 Detail of identified methods, blue lines are *impact-based* methods, white line are *hazard-based* methods, purple are methods that are both *hazard-based* and *impact-based*, HRED corresponds to the 4 steps in the cause-to-effect chain (H: Hazard, R: Risk, E: Effect, D: Damage) with grey cell being the steps not included. ETID stands for Exposure to Impact Delay (cont. and end)

Authors	**Paper title**	**Hazards covered**	**Damage covered**	**Covered steps of the cause-to-effect chain**				**CF availability**	**CF resolution**	**Link to Life Cycle**
Golsteijn, Huizer, Hauck, van Zelm et Huijbregts (2014)	Including exposure variability in the life cycle impact assessment of indoor emissions: The case of metal degreasing	Chemical (inhalation)	cancer and non-cancer illness, long ETID	H	R	E	D	-	Process / Activity	None
Cucurachi et Heijungs (2014)	Characterization factors for life cycle impact assessment of sound emissions	Noise	no impact assessment	H	R	E	D	+	Spatialized (10km2 cell)	None
Scanlon et al. (2014)	An Approach to Integrating Occupational Safety and Health into Life Cycle Assessment: Development and Application of Work Environment Characterization Factors	All for which data are available	All for which data are available, short and long ETID	H	R	E	D	+ / -	Industry	Mapping to LCA inventory
Kikuchi, Y. et al. (2014)	Design of recycling system for poly(methyl methacrylate) (PMMA). Part 2: process hazards and material flow analysis	Chemical (inhalation)	no impact assessment	H	R	E	D	-	Process	None
Hosseinijou et al. (2014)	Social life cycle assessment for material selection: a case study of building materials	All for which data are available (exclude illnesses)	no impact assessment	H	R	E	D	-	Company	None
Kijko, Gaël, Jolliet, Partovi-Nia, Doudrich et Margni (2015)	Occupational health impacts of organic chemical exposure: the product life cycle perspective	Chemical (inhalation)	cancer and non-cancer illness, long ETID	H	R	E	D	+	Industrial sector	None
Kijko, G. et al. (2016)	Occupational health impacts of organic chemical exposure: the product life cycle perspective	Chemical (inhalation)	cancer and non-cancer illness, long ETID	H	R	E	D	+	Economic sector	I-O model
Eckelman (2016)	Life cycle inherent toxicity: a novel LCA-based algorithm for evaluating chemical synthesis pathways	Chemical	cancer and non-cancer illness, long ETID	H	R	E	D	+	Product	None

Error! Reference source not found. provides a snapshot of the identified methods. Each line orresponds to a published method to include parts or all of OHS in LCA. Most identified methods have been published in a peer-reviewed science journal, the two exceptions are Schmidt, A. et al. (2004), a report published by the Danish Environmental Protection Agency and Hendrickson et al. (2006), which was published as a book chapter. Blue lines identify *hazard-based* methods, white lines are *impact-based* methods and purple lines publication that provide both *hazard-based* and *impact-based* methods. The CF availability refers to the publication of CF by the authors, making the application of the method possible. + means the CF are fully provided by the authors, +/- means that part of the CF are available and – means the CF are not provided. The CF resolution corresponds to the level of detail provided by the CF: the most detailed are activity/process specific and the more aggregated are country-specific. The hazards and damages covered (based on Figure 2.3) by each method are also presented. When an impact assessment is included (that is when the method do not stop at the exposure assessment), *impact-based* method coverage of hazards and damages only depend on the data availability and usually covers most hazards and damages. *Hazard-based* methods are, by definition, more hazard specific and usually cover only one hazard and only long ETID damages. The last column describes any links to a life-cycle perspective. Most *impact-based* methods map their CFs to LCA inventory databases (four out of seven), two use an I-O model. Of the 11 *hazard-based* methods, only three provide such a link, all by relying on an IO model.

None of the published methods have all the characteristics of an ideal method described in the introduction: methods with the largest coverage of hazards, exposures, and impacts lacks the granularity required to differentiate between those hazards, exposures and impacts. The most specific methods often lack a link to a life cycle perspective or the data needed to generalize the CF. If mapped onto the two classifications presented in Figure 2.3, *hazard-based* methods cover only two hazards: chemical (exclusively via breathing) and noise exposure. Most *impact-based* methods cover all hazards for which data are available, including exposure to physical hazards.

2.2.4 Discussion

2.2.4.1 Limitations of existing methods

Impact-based methods use national injury and illnesses statistics that are accessible in many countries, making it possible to generate country-specific or aggregated (e.g., OECD) CFs. However, those statistics depend on national regulations: they only account for occupational injuries and illnesses tracked by regulatory agencies and declared by the employer. For instance, depending on country specific regulations, the definition of work-related injury or illness related to transport may vary, with some countries including injuries caused by transport accidents to and from work. It is worth noting that Europe and US recently made the effort to produce comparable aggregate fatal work injuries statistics (Wiatrowski & Janocha, 2014). Further work is also needed to expand the existing methods at a global scale: despite the fact that data are usually available at a country level (when available at all), a product life-cycle covers usually more than one country. The declaration process also leads to a general undercounting (Hofstetter & Norris, 2003), and a particular undercounting for hazards with long ETID such as carcinogenic chemicals and ionizing radiations, as the link to specific occupational exposures can be difficult to identify. The data on which *impact-based* methods rely, in contrast, systematically undercount injuries and illnesses and are not consistent across reporting agencies as already pointed out in the literature (Azaroff, Levenstein, & Wegman, 2002; Hendrickson et al., 2006; Hofstetter & Norris, 2003; Leigh, Marcin, & Miller, 2004; Probst, Brubaker, & Barsotti, 2008). For instance, the data reported by the Bureau of Labor Statistics does not include data on self-employed and federal government workers (Bureau of Labor Survey, 2016).

Hazard-based methods also rely on available data. For instance, (Kijko, Gaël et al., 2015) use data from the US Occupational Safety and Health Administration that was not specifically built for modeling human health damages in LCIA and may not be consistent across countries. *Hazard-based* methods require two main components to model potential impacts on human health throughout the whole life cycle: a well-defined cause-to-effect chain and a database of emission / exposure levels. In general, chemical hazards have been studied for a long time and are there are databases of emissions and concentration made available by government agencies. But the cause-to-effect chain is not fully known in detail: with new toxicological pathways such as the epigenetic (Wild, C. P., 2005; Wild, Christopher Paul, 2012), synergism/antagonism between chemicals toxicological pathways and emerging chemicals, such as the nanoparticles (Walker, Bosso, Eckelman, Isaacs, & Pourzahedi, 2015). Also, no existing *hazard-based* method assesses the potential impacts linked to short ETID.

A shared challenge for both *hazard-based* and *impact-based* methods is the (limited) data availability and (low level of) coherence at a global scale. The datasets provided by national public agencies do not necessarily use the same industrial classifications or cover the same occupational injury/illnesses or measure the same chemical concentrations. Also, due to the use of different production system technologies and the difference in OHS regulations, using one country as a proxy for all the others may not be acceptable on the long run.

Finally, OHS issues are also addressed in sLCA. For instance, Benoit et al. has advanced approaches for evaluating worker health and safety aspects in the Social LCA Guidelines for sLCA (Benoît et al., 2010). While OHS would be an important aspect to consider in both eLCA and sLCA, this could lead to potential double counting if both eLCA and sLCA OHS indicators are jointly used, aggregated or compared directly to support decision making. The distinction between eLCA and sLCA does not mean that they are incompatible and methods to include OHS in eLCA may be used in sLCA.

2.2.4.2 Opportunities:

Some sophisticated *hazard-based* methods are well adapted to provide a robust assessment of specific activities such as the methods developed by Golsteijn et al. (2014), Hellweg et al. (2009); Hellweg et al. (2005), or Demou et al. (2009) to assess exposures to chemicals by inhalation at a workplace. Because of intensive data requirement they cannot be easily applied to assess the occupational exposures of all the activities of a product life-cycle. Nevertheless, we see the opportunity to couple such sophisticated methods assessing key foreground activities of a given life cycle stage with a more generic and less data intensive method extending the analysis for the remaining activities throughout the life cycle such as the method developed by Kijko, G. et al. (2016). The combination of those methods makes it possible have a life-cycle perspective while being able to use very specific data when available.

A second opportunity is the possibility to rely on *impact-based* methods wherever a *hazard-based* method has not been developed.

2.2.4.3 Proposed framework

The review and analysis of the existing methods has identified a variety of hazards and damages that cannot be captured by a single method. A framework combining the different methods is needed to consistently structure the integration of OHS in LCIA.

Figure 2.4 presents the proposed framework for the inclusion of OHS in LCA. It consists of two main parts: the first considers the impacts with long ETID in a similar way as Human Health impact modeling in LCA, and a second part considering the impacts with a short ETID. Both part consider all existing occupational hazards and provide quantify impacts in as number of cases, DALYs, or any other unit that can be converted to cases or DALY. The first part consists of many different *hazard-based* methods that are hazard-specific and rely on a cause-to-effect model linking hazard to impact, with long ETID, on worker health. The second part consists of one *impact-based* method using impact data (OHS statistics) linked to impacts with short ETID.

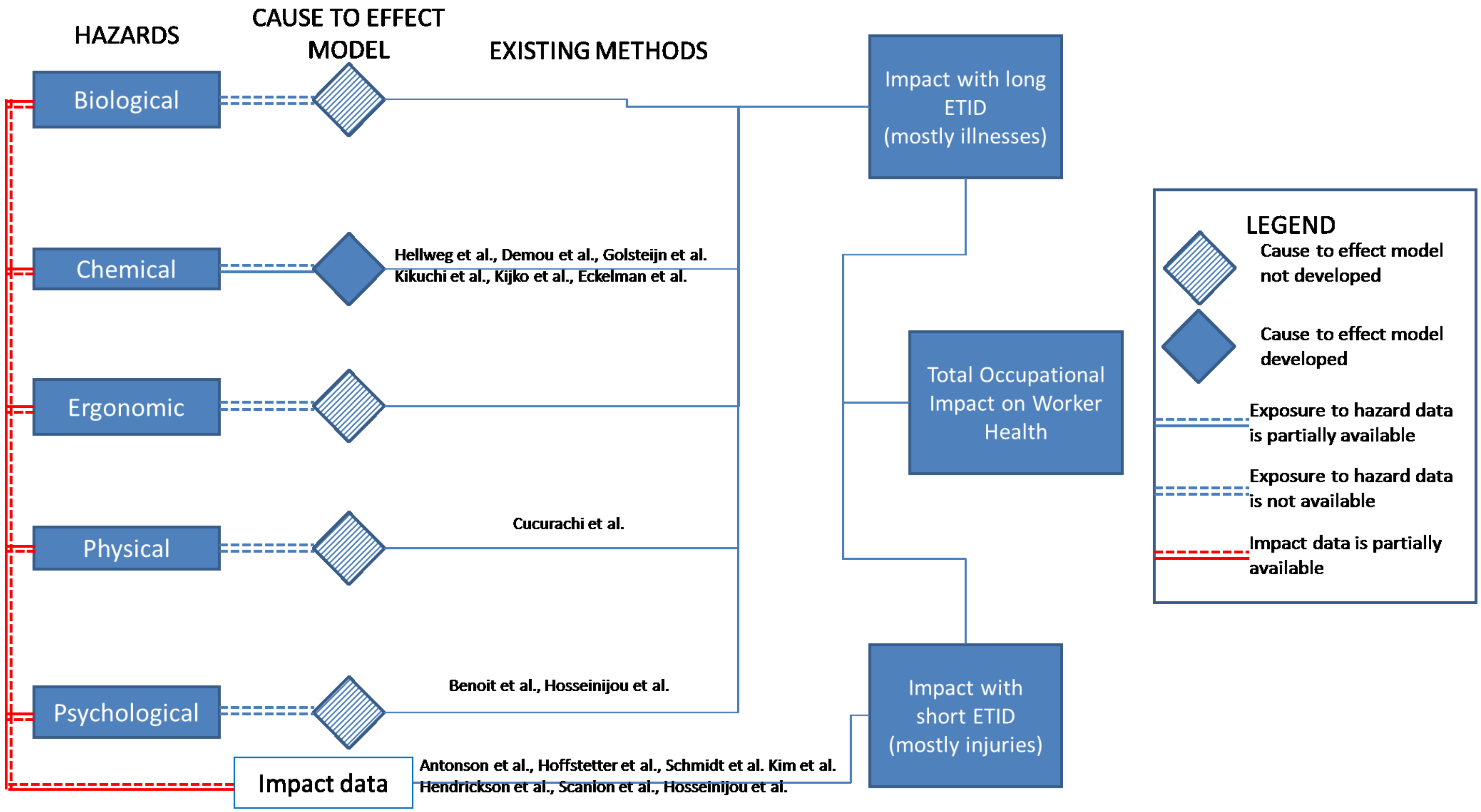


Figure 2.4: Framework for inclusion of OHS in LCA with availability of hazard exposure or risk data, cause-to-effect model, methods and impact data

2.2.4.4 Recommendations:

The work environment should become a focus for the UNEP-SETAC Life-Cycle Initiative: building a consensus among the LCA scientific community on the integration of OHS in LCA may be the best way to push for the development and implementation of standardized, consistent methods focusing on worker health.

2.2.4.4.1 For the method developers:

The focus of method development should be oriented toward the main causes of impact on workers as presented in Figure 2.1, with a priority on the development of *hazard-based* methods when the cause-to-effect chain and the data needed to evaluate exposures are available. In decreasing order of priority, following the GBD, method development should be oriented toward chemical and physical hazards such as ergonomic stressors and noise hazards.

We propose the following guidance for the development of individual methods to ensure consistency with each other and with the general LCA framework:

- A method should provide indicators with units compatible with the current recommendations for human health indicators (Frischknecht et al., 2016), i.e. cases of illnesses, DALY or units that can be converted to it. For the exposure to chemicals, the use of the effect and severity factors provided by the USEtox consensus model is recommended (Rosenbaum, R. et al., 2008; Rosenbaum, Ralph K. et al., 2011).
- Each method has to explicitly identify the hazards effects and exposure route covered to facilitate the detection of potential double counting with other methods and uncovered hazard / effect.
- A method should provide detailed CFs for each combination of hazard / effect to facilitate the joint use of different methods.
- The full set of CFs should be provided, with uncertainty data, along with the method.

In addition to the above guidance we also recommend the creation of a comprehensive list of data sources (injury and illnesses statistics, concentration measurements, noise level…) for the work environment to facilitate the generation of CFs at country level as national variability may be an important source of uncertainty.

2.2.5 Conclusion

This article has identified the literature relevant to the inclusion of OHS in LCA. The literature review has shown that even if we are not yet able to capture the complete extent of occupational impacts on workers in LCIA, the existing methods provide a good base on which the future methods can be built. The set of criteria defined in the method section and the framework proposed in the discussion helped identify the main method types and a potential to combine different methods to better cover impacts due to a specific hazard. The framework proposed a way to combine the different existing methods while highlighting the types of workplace hazards for which more work is needed.

CHAPITRE 3: PROBLEMATIQUE ET OBJECTIFS DE RECHERCHE

3.1 Problématique

Aujourd'hui il n'existe pas encore d'approches suffisamment complètes et opérationnelles pour évaluer les impacts potentiels sur la santé des travailleurs des expositions professionnelles aux substances toxiques en Analyse du Cycle de Vie. La plupart des méthodes proposées jusqu'à présent souffrent d'un manque de données rendant impossible l'extension à l'échelle d'un cycle de vie et/ou à l'ensemble des secteurs ou des systèmes de produits généralement considérés dans les bases de données d'inventaire du cycle de vie (Demou et al., 2009; Golsteijn et al., 2014; Hellweg et al., 2009; Hellweg et al., 2005; Hofstetter & Norris, 2003). Il existe des approches basées sur des statistiques sectorielles d'accidents et de maladies professionnelles qui, bien que couvrant la plupart des sources d'impact sur la santé des travailleurs, sous-estiment systématiquement les chiffres réels (Azaroff et al., 2002; Hendrickson et al., 2006; Hofstetter & Norris, 2003; Leigh et al., 2004; Probst et al., 2008). Cette sous-estimation est encore plus importante pour les impacts chroniques, c.-à-d. ayant des effets à long-terme sur la santé humaine car le lien entre l'effet et une cause professionnelle est encore plus dur à prouver.

Il y a donc besoin de développer une méthode d'évaluation des impacts sur la santé des travailleurs des expositions professionnelles aux polluants. Cette méthode doit être opérationnalisable dans la pratique de l'ACV , c.-à-d. : être compatible avec les approches ACV existantes pour évaluer les émissions en milieu extérieur et doit reposer sur des données suffisamment complètes et disponibles pour permettre son utilisation à l'échelle d'un cycle de vie.

3.2 Objectifs de recherche

L'objectif général de ce projet de recherche est de développer et rendre opérationnelle une méthode d'évaluation des impacts liés aux exposition professionnelles par inhalation aux polluants, de manière cohérente et comparable avec les impacts des émissions extérieures déjà intégrés et évalués en ACV.

Objectifs spécifiques :

1. Développer une méthode, se basant sur des concentrations mesurées, permettant d'évaluer les impacts potentiels liés à l'exposition aux substances chimiques organiques en milieu professionnel dans l'ensemble des secteurs de l'industrie manufacturière des États Unis.

   L'objectif 1 répond aux questions de recherche suivantes :

   a. Quel est l'impact potentiel sur la santé humaine par heure de travail dans chaque secteur industriel et comment se comparent-ils?

   b. Quels sont les secteurs manufacturiers avec le potentiel d'impact le plus important sur la santé des travailleurs, compte tenu de l'ensemble des heures travaillés dans chaque secteur?

   c. Quelles sont les substances les plus impactantes ?

   d. Quelles sont les incertitudes associées ?

2. Étendre l'approche développé à l'objectif 1 à l'ensemble de la chaine d'approvisionnement d'une entreprise ou secteur industriel pour couvrir l'ensemble du cycle de vie.

   L'objectif 2 répond aux questions suivantes :

   a. Comment prendre en compte les impacts potentiels sur les travailleurs à l'échelle d'une chaîne de valeur ?

   b. Comment se comparent les impacts potentiels au sein des secteurs vis-à-vis de leur chaîne de valeur aux États-Unis ?

3. Appliquer la méthode développée en 2 et comparer ses résultats aux autres étapes de l'analyse du cycle de vie ainsi qu'aux autres impacts sur la santé humaine au travail.

   L'objectif 3 répond aux questions suivantes :

   a. Comment se comparent les impacts sur l'exposition des travailleurs avec ceux des émissions extérieures dans une ACV de produit ?

   b. Comment évaluer le degré de certitude de l'importance des impacts potentiels d'une étape du cycle de vie vis-à-vis aux autres ?

    c. Est-il pertinent d’inclure les impacts sur l’exposition des travailleurs en ACV ?

4. Étendre l’approche aux substances inorganiques et métaux

   L’objectif 4 répond à la question suivante :

    a. Comment se comparent les impacts de l’exposition des travailleurs aux substances organiques aux polluants organiques tels que les PM et les métaux ?
    b. Comment étendre l’approche à plus de substances organiques ?

CHAPITRE 4: DÉMARCHES DE L'ENSEMBLE DU TRAVAIL DE RECHERCHE ET ORGANISATION DU TRAVAIL

Afin de guider le lecteur à travers la méthodologie du projet dans sa globalité, les grandes lignes vont être présentées ci-après. Les détails de la méthodologie sont fournis dans les deux chapitres suivants sous la forme d'article scientifique.

La Figure 4.1 présente une vue générale de la méthode développée pour répondre à la problématique et aux objectifs de recherche.

La méthodologie pour adresser les impacts potentiels des travailleurs à l'exposition de polluants en milieu de travail a été développée pour le cadre géographique des États-Unis. Ce choix est justifié par la disponibilité des données. Il est important de noter que tout au long de cette thèse, le terme *impact* faire directement référence à des impacts potentiels tels que définit dans la norme ISO 14040 (International Organization for Standardization, 2006).

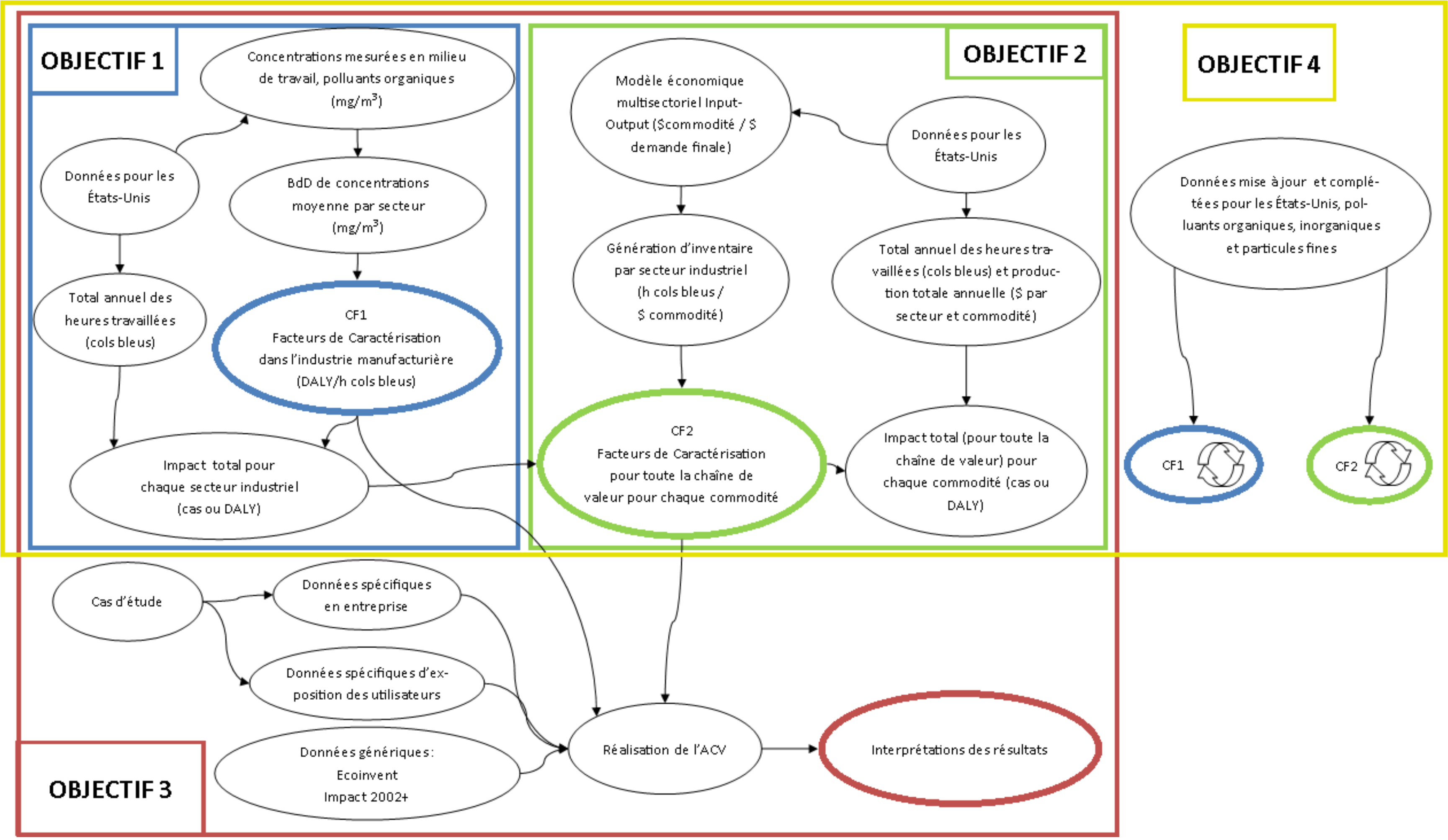


Figure 4.1 : Étapes et organisation de la méthode pour répondre au 4 objectifs de recherche

4.1 Calcul des facteurs de caractérisation dans l'industrie manufacturière

La première partie de la méthodologie se concentre sur la génération de FC spécifiquement développés pour caractériser l'intensité des impacts sur la santé humaine de chaque heure de travail dans chaque secteur industriel des États-Unis. Pour ce faire, la base de données de concentration de polluants mesurée en milieu de travail aux États-Unis (base de données *Chemical Exposure Health Data* (United States Occupational Health and Safety Agency, 2015)) est analysée pour identifier les mesures correspondant aux expositions individuelles des travailleurs. Des concentrations d'exposition moyennes (et leur variabilité) ont été calculées pour chaque substance dans chaque secteur industriel.

Les CF exprimant un impact potentiel sur la santé humaine par heure travaillée sont calculés par le produit entre les concentrations d'exposition des travailleurs à une substance i dans un secteur j (C_{ij} en mg/m^3), leur débit respiratoire dans le secteur j (BR_j en m^3/h) et l'effet sur la santé humaine de la substance i (EF_i en DALY ou cas/mg) d'une telle exposition :

$$CF1_{ij} = EF_i \times BR_j \times C_{ij} \tag{4.1}$$

Le débit respiratoire définissant la quantité horaire d'air respirée par un travailleur col bleu, est tirée du manuel des facteurs d'exposition (United States Environmental Protection Agency, 2011). Les facteurs d'effet (EF) proviennent de USEtox (Rosenbaum, Ralph K. et al., 2011).

Une application aux secteurs manufacturiers de l'industrie Américaine est réalisée en utilisant le total des heures travaillées dans chaque secteur. Seules les heures de travail correspondant aux travailleurs cols bleus sont considérées, les travailleurs cols bleus étant des employés de production sans fonction de management.

Un des défis à relever est de rendre cohérentes les données qui sont fournies dans différentes classifications industrielles. Finalement, une analyse d'incertitude prenant en compte l'incertitude sur les concentrations mesurées et sur les facteurs d'effet permet d'obtenir un intervalle de confiance pour chaque CF.

Cette méthode a fait l'objet d'un article publié en 2015 accompagné de CF pour l'exposition aux polluants organiques aux États-Unis entre 2002 et 2009, voir le Chapitre 5.

4.2 Calcul des facteurs de caractérisation pour toute la chaîne de valeur

La génération de CF pour les expositions professionnelles aux polluants organiques dans chaque secteur manufacturier est un premier pas dans la direction de l'intégration des impacts sur la santé des travailleurs en ACV. Toutefois cela n'est pas suffisant pour intégrer la vision cycle de vie : un praticien ACV devrait d'abord déterminer l'inventaire de toutes les heures travaillées dans chaque secteur industriel à l'échelle du cycle de vie de l'unité fonctionnelle considéré et caractériser le score d'impact avec les CF propre à chaque secteur industriel calculé auparavant. Actuellement, aucun outil ou base de données actuel ne permet de générer directement un tel inventaire.

L'analyse économique input-output (I-O) est un outil adapté à la modélisation des liens économiques multisectoriels. Le cœur de cet outil est une matrice A composé d'éléments a_{ij} indiquant la quantité de commodité i directement nécessaire à la production d'un $ de commodité j. Selon la théorie de Leontief l'inversion de la matrice (I-A) permet de reconstruire l'inventaire des productions nécessaires de la part de chaque secteur à travers toute la chaîne de valeurs (Leontief, 1986) :

$$\vec{X} = (I - \boldsymbol{A})^{-1} \times \vec{Y} \tag{4.2}$$

Dans l'équation 4.2, $\vec{X}$ correspond à la production totale nécessaire de chaque commodité (en $) pour répondre à la demande finale $\vec{Y}$ (en $) en prenant en compte l'intégralité des chaînes de valeur.

En se basant sur le nombre total d'heures de travail, la production totale de chaque secteur, la production totale de chaque commodité ainsi que sur une table de production (fournissant le détail de la production de chaque commodité par chaque secteur) on obtient une matrice $\boldsymbol{B}$ présentant le nombre d'heures travaillées dans chaque secteur par $ de production de chaque commodité sur l'ensemble de la chaîne de valeur. Le nombre d'heures totales travaillées s'obtient alors en multipliant la matrice $\boldsymbol{B}$ par la valeur totale de production de chaque commodité $\vec{X}$ (voir équation 4.3).

$$\vec{h} = \boldsymbol{B} \times \vec{X} \tag{4.3}$$

L'équation 4.4 montre comment obtenir les facteurs de caractérisations pour la chaine de valeur à partir des facteurs de caractérisations obtenus dans la première partie du projet de recherche.

$$\overrightarrow{CF2} = \overrightarrow{CF1} \times \boldsymbol{B} \times (\boldsymbol{I} - \boldsymbol{A})^{-1} \tag{4.4}$$

L'incertitude des CF1 développés au point précédents est propagée afin d'obtenir des CF2 pour la chaîne de valeur avec des intervalles de confiance.

La méthode pour calculer ces CF pour l'exposition des travailleurs aux polluants organiques à travers toute la chaine de valeurs de chaque commodité aux États-Unis a fait l'objet d'un article publié en 2016 (Kijko, G. et al., 2016) accompagné de CF fournis en information supplémentaire voir CHAPITRE 6: .

4.3 Cas d'étude

Afin d'évaluer l'application de la méthode développée aux deux points précédents, un cas d'étude est réalisé. Le but est de démontrer que la méthode développée est applicable sur un cas réel et de comparer les impacts potentiels sur les travailleurs obtenus avec les autres impacts potentiels sur la santé humaine pris en compte en ACV.

Le cas d'étude est un fauteuil de bureau pour lequel un partenaire industriel a fourni (sous couvert de la signature d'un accord de confidentialité) des données relatives à :

- la composition du fauteuil ;
- les étapes de fabrication du fauteuil ;
- les heures travaillées sur le site de production du partenaire ;
- les concentrations de polluant dans les ateliers de fabrication du partenaire ;
- les taux d'émission de polluant du produit finit.

L’unité fonctionnelle prise en compte est « L’utilisation d’un fauteuil de bureau pendant 5 ans dans un environnement professionnel ».

La base de données utilisée pour modéliser l’inventaire du cycle de vie est Ecoinvent v2.2. Le logiciel utilisé est Simapro 8.0.4.30.

Les méthodes d’évaluation des impacts du cycle de vie utilisées sont :

- Impact 2002+ pour caractériser les émissions extérieures tout au long du cycle de vie du produit ;
- un modèle composé d’un compartiment homogène (Hellweg et al., 2009) pour calculer les concentrations d’exposition des utilisateurs avec hypothèse une décroissance de premier ordre (Guo, 2002a, 2002b) des facteurs d’émission du fauteuil.

L’incertitude est prise en compte par l’utilisation de la méthode de Monte Carlo pour analyser la propagation de l’incertitude aux scores d’impact.

L’étude de cas et l’analyse de la propagation de l’incertitude a fait l’objet de l’article publié en 2015 mentionné au chapitre précédent et présenté au chapitre 6.

4.4 Mise à jour et extension de la méthode à d’autre polluants

La méthode développée et testée aux points précédents ne couvre que les polluants organiques pour lesquels un facteur d’effet est disponible dans USEtox. Afin de proposer des facteurs de caractérisations à jours, les CF1 et CF2 sont générés à partir des concentrations en milieu de travail fournie par l’OHSA (United States Occupational Health and Safety Agency, 2015) en prenant en compte tous les polluants pour lesquels un facteur d’effet existe dans USEtox.

Cette extension fait l’objet du chapitre 7.

L’extension de la méthode pour utiliser d’autres sources de facteur d’effet pour les substances non inclues dans USEtox est évaluée en utilisant la base de données d’enregistrement, d’évaluation, d’autorisation et de restriction des substances chimiques (REACH) des dossiers de déclarations des substances chimiques distribuées ou produites au sein de l’Union Européenne.

CHAPITRE 5: ARTICLE 2: IMPACT OF OCCUPATIONAL EXPOSURE TO CHEMICALS IN LIFE CYCLE ASSESSMENT: A NOVEL CHARACTERIZATION MODEL BASED ON MEASURED CONCENTRATIONS AND LABOUR HOURS

5.1 Présentation de l’article

Cet article, publié le 16 Juin 2015 dans le journal *Environmental Science and Technology* présente les travaux de recherche effectués en réponse au deuxième objectif du projet de recherche.

Cet article présente une nouvelle approche méthodologique pour calculer les impacts potentiels sur la santé des travailleurs des expositions aux polluants organiques par voie respiratoire. Un ensemble de facteurs de caractérisation dans le contexte des États-Unis.

Les informations supplémentaires soumises avec l’article sont disponibles dans l’Annexe B et à l’adresse suivante : http://pubs.acs.org/doi/suppl/10.1021/acs.est.5b00078.

Auteurs : Gaël Kijko, Olivier Jolliet, Vahid Partovi Nia, Greg Doudrich, Manuele Margni.

5.2 Manuscrit

5.2.1 Introduction

Relevance of considering occupational health in life cycle impact assessment (LCIA)

LCIA is a comparative tool designed to evaluate the potential impacts of products or services throughout their entire life cycles (Hauschild, Michael Z., 2005), multiplying inventory flows per functional unit by life cycle impact assessment (LCIA) characterization factors (CF). One of the main aims of LCIA is to avoid burden shifting between different life cycle stages or impact categories (European Commission Institute for Environment and Sustainability - Joint Research Center, 2010a). However, for toxic emissions, LCIA has traditionally focused on the potential impacts of outdoor emissions, disregarding potential impacts and impact shifts related to occupational health, which can be significant. According to Lim et al. (2012), harmful chemicals cause over 370 000 premature occupational deaths every year around the world. It is therefore crucial to include occupational impacts in integrated product policies and thus into tools such as LCIA, which aim to reduce a system's total impact (Hofstetter & Norris, 2003) and complement sector-specific risk assessment (Grieger et al., 2012) through approaches that cover the entire life cycle of a product.

Occupational impact in LCIA

The rationale for including occupational health impacts has been thoroughly discussed by Hofstetter et Norris (2003): the main reason for this inclusion is to avoid burden shifting from general population environmental impacts to worker health. Several research efforts have attempted to include occupational impacts within the LCIA framework, combining work statistics on illness and death in occupational environments to determine the human health impacts of working activities in each industrial sector (Antonsson & Carlsson, 1995; Hauschild, M. Z. & Wenzel, 1997; Kim & Hur, 2009; Scanlon et al., 2014; Schmidt, A. et al., 2004). Although they cover all industrial sectors, these methods have several drawbacks—specifically the fact that using data that relies on a two-step process (declaration and acknowledgement) induces a significant risk of undercounting (Hofstetter & Norris, 2003). Methods building on sector-based illness and accident statistics are not chemical specific and do not necessarily encompass long-term chronic illnesses that occur after retirement age.

Other methods mainly focus on modeling the fate and exposure of chemicals in work environments in the same way as environmental LCIA models outside environmental fate and pollutant exposure. Hellweg et al. (2009) performed a review of existing models, recommending the use of a simple one-box model for generic LCA applications. Several case studies applied such fate and exposure models to predict exposure concentrations and intakes in an LCIA context (Demou et al., 2009; Golsteijn et al., 2014; Hellweg et al., 2005; Meijer, Huijbregts, & Reijnders, 2005a, 2005b), focusing on a few core processes without addressing the entire supply chain. In practice, it is extremely difficult to collect the number and type of required parameters, hindering the broad applicability of the modeling approach in LCIA. On one hand, the one-box model recommended by Hellweg *et al.* (2009) may make it possible to assess the occupational exposure of white collars workers ("a person whose job is professional or clerical and usually salaried"

(Collins, 2015b)) associated with well-defined volatile organic compound (VOC) emissions from office furniture such as formaldehyde (Plaisance, Blondel, Desauziers, & Mocho, 2014). On the other hand, such a simplified generic model is not suitable to assess the occupational exposure of blue collars workers ("a manual industrial worker" (Collins, 2015a)) over life cycle stages (e.g. including plastic and wood manufacturing for office furniture) since emissions factors are generally unknown and working environments are very heterogeneous in terms of ventilation rate and geometry. Also, these parameters are difficult to collect across sectors.

Hellweg et al. (2009) suggested that the use of a model could be circumvented by directly relying on measured concentrations rather than emissions to assess chemical exposure. Multiple studies in the field of industrial hygiene analyze organic chemical concentrations, studying exposure levels and regulation compliance within individual industrial sectors (Kauppinen et al., 2006; Witter, Tenney, Clark, & Newman, 2014). In a recent article, Collinge, Landis, Jones, Schaefer et Bilec (2013) presented a method using concentration measurements to assess the potential indoor impact in green building rating systems. Walser, Juraske, Demou et Hellweg (2013) provides an interesting case study for the printing industry based on data collected over several decades, and Kikuchi, Yasunori et Hirao (2008) used measured concentrations in an LCIA/RA case study of metal degreasing processes. However, these studies were only applied to assess certain individual industry sectors. Demou, Hellweg et Hungerbühler (2011) compared 38 organic solvents based on their average measured occupational concentrations across all sectors, potential exposed populations and effect factors, but aggregation across all sectors does not make it possible to assess a product manufactured in a given sector within its specific supply chain. In a search to provide measured concentrations for each manufacturing sector across the entire industry, an interesting data source was identified: the Chemical Exposure Health Data (United States Occupational Health and Safety Agency, 2015) set out by the U.S. Occupational Safety and Health Administration (OSHA), which provides measurements for the entire manufacturing industry collected to verify compliance with occupational limit values (OLV) and distinguishes between concentrations from different periods. There is therefore a need to build upon this database in order to provide characterization factors to consistently estimate exposure intensity in individual sectors throughout the entire manufacturing industry to characterize the entire life cycle of a product from an occupational perspective.

This article aims to develop a characterization model and factors for occupational exposure to organic chemicals for all individual industrial sectors, in keeping with the LCIA framework. More specifically, this paper aims to (a) develop a framework and model to assess the occupational exposure of blue-collar workers to individual chemicals based on concentrations in each sector and labour hours per functional unit, (b) build on the OSHA database and establish sets of sector-specific generic occupational concentrations for a wide range of organic substances across the U.S. manufacturing industry for the post-2000 period, (c) provide chemical-specific characterization factors or impact intensity per hour worked in each U.S. manufacturing sector and (d) evaluate this novel approach by providing CF uncertainty ranges and assessing the magnitude of the total burden of disease (cancer and non-cancer) due to organic chemicals in each sector and across the U.S. manufacturing industry.

5.2.2 Methods

5.2.2.1 Characterization framework for outdoor and indoor emissions

The widely accepted LCIA source-to-impact framework to assess toxic emissions was used as the starting point for this study (Jolliet et al., 2006). For outdoor and indoor emissions, the impact per functional unit D_{ei} (DALY/FU) for effect e (cancer or non-cancer) caused by chemical i is the product of the amount of chemical i emitted per functional unit E_i ($kg_{emitted}$/FU) and the characterization factor CF_{ei} (DALY/$kg_{emitted}$), where the characterization factor is the product of EF_{ei} the effect factor (DALY/kg_{intake}) and iF_i the intake fraction ($kg_{intake}/kg_{emitted}$):

$$D_{ei} = CF_{ei} \times E_i = EF_{ei} \times iF_i \times E_i = EF_{ei} \times I_i \tag{5.1}$$

This impact score can also be expressed as the product of I_i the intake per functional unit of chemical i (kg_{intake}/FU) and EF_{ei} the effect factor (DALY/kg_{intake}). The effect factor is expressed by the product of DR_{ej}, the human dose-response for effect e caused by chemical i (cases/kg_{intake}) that accounts for lifetime exposure, multiplied by SF_e, the severity factor for cancer and non-cancer effects equal to 11.5 and 2.7 (DALY/cases), respectively (Huijbregts et al., 2005).

5.2.2.2 Characterization framework for occupational health

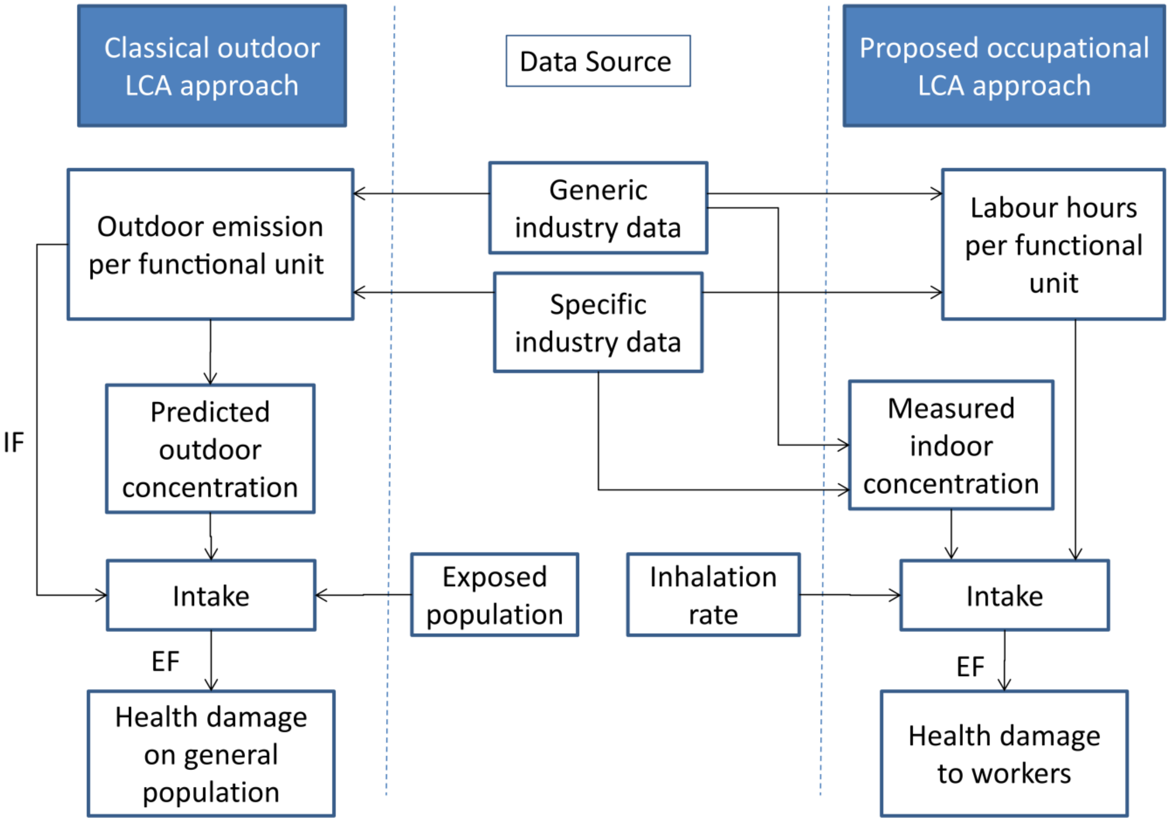


Figure 5.1: Comparison and links between the general LCIA framework and the proposed occupational approach

Since occupational emissions and intake fractions are not readily available across all sectors, this paper advances an alternative approach to assess occupational exposure for LCIA (Figure 5.1). Occupational concentrations are widely measured by work inspection (Occupational Safety and Health Administration (OSHA) in the U.S.) as part of regulatory enforcement activities. Inspections may include personal air sampling to determine the exposure of workers to regulated chemicals. Thus, the damage was also calculated as the product of intake and effect factor. But instead of using an emission as a starting point, the method proposes to determine the intake as a function of the measured occupational concentration and the number of production worker hours per functional unit. Equation 5.1 was therefore modified to calculate the sector-specific chemical intake I_{ij} (kg/FU) as the product of BR_j (m^3/h), the breathing rate of workers in sector j, C_{ij} (kg/m^3), the concentration of pollutant i in sector j to which the workers are exposed, and h_j (h/FU), the number of blue-collar worker hours exposed per functional unit in manufacturing sector j. The impact on human health per functional unit for effect e caused by chemical i in sector j D_{eij} (DALY/FU) becomes:

$$D_{eij} = EF_{ei} \times I_{ij} = CF'_{eij} \times h_j = EF_{ei} \times BR_j \times C_{ij} \times h_j \tag{5.2}$$

where:

h_j (h/FU) is the number of blue-collar worker hours exposed per functional unit in manufacturing sector j and CF'_{eij} is the modified characterization factor or impact intensity per blue-collar worker hour worked for effect e caused by chemical i in sector j, expressed in (DALY/h), determined as:

$$CF'_{ij} = EF_i \times BR_j \times C_{ij} \tag{5.3}$$

Expressed in DALY/h, these characterization factors can be aggregated within a sector by summing CFs across chemicals. The total burden of disease (TBD) related to occupational exposure (overall impact due to chemicals across all industrial manufacturing sectors during one year of operation) can also be obtained by summing the CF'_{eij} across all chemicals, sectors and effect types (cancer and non-cancer) multiplied by the respective total yearly blue-collar worker labour hours within each sector j: h_j^{tot} (h/year).

$$TBD = \sum_e \sum_j \sum_i CF'_{eij} \times h_j^{tot} \tag{5.4}$$

This paper primarily aims to provide and analyze generic concentrations, related intake intensities and characterization factors for the multiple combinations of organic chemicals and manufacturing sectors in the U.S. for both cancer and non-cancer impacts. Though the study does not aim to provide the inventory data (i.e. worker hours per functional unit), production hour statistics in each manufacturing sector were collected and used to calculate and aggregate average characterization factors across the U.S. economy.

5.2.2.3 Application to the U.S. manufacturing industry

The proposed framework was applied to all U.S. manufacturing sectors: industrial sectors were determined according to the 2007 North American Industry Classification System (NAICS). There are four levels of classification: three to six digits, three being the most aggregated level and six the most detailed. For example, sector 3253 (*Pesticide, Fertilizer, and Other Agricultural Chemical Manufacturing*) is a NAICS level 4 sector that aggregates two NAICS level 5 sectors, 32531 (*Fertilizer Manufacturing*) and 32532 (*Pesticide and Other Agricultural Chemical Manufacturing*), and is attached to a NAICS level 3 sector: 325 (*Chemical Manufacturing*). The industrial manufacturing sectors are classified between sectors 311 and 333.

According to Equation 5.2, three sector-specific parameters must be collected to calculate the potential impacts per sector: chemical concentration (measured or generic), breathing rate and production hours worked per functional unit. An average worker breathing rate value of 1.6 m^3/h was assumed (United States Environmental Protection Agency, 2011). The chemical-specific EFs were provided by the USEtox consensus model (Rosenbaum, R. et al., 2008; Rosenbaum, Ralph K. et al., 2011).

5.2.2.4 Concentration of organic chemicals in U.S. manufacturing industry sectors

OSHA Chemical Exposure Health Data (CEHD) was used for the measured concentration data (United States Occupational Health and Safety Agency, 2015). These data are partially classified by NAICS (2002 version) and SIC (Standard Industrial Classification, the former U.S. classification system). The CEHD database was screened to extract sector-specific measured concentrations from 2002 to 2009 in order to best capture exposure levels measured with improved detection capabilities and cover a period that is coherent with the timeframe of the other variables, such as the labour hours. In total, 403 421 measurements for 602 chemicals were available. Only "personal" measurements for organic chemicals with available USEtox effect factors were selected, for which characterization factors could be calculated. According to OSHA, "personal sampling results representt the exposure to the individual who was actually wearing a sampling device" (United States Occupational Health and Safety Agency, 2015) thus accounting for exposure without personal protection. Working with personal measurements instead of "area" measurements makes it possible to bypass the emission-mixing-protection-exposure framework and work directly with exposures. The 17 measured concentrations that exceeded the *immediately dangerous for life and health* (United States National Institute for Occupational Safety and Health 1994) level were excluded since they cannot be reasonably representative of usual worker exposure. The filtered data was then transposed to the NAICS 2007 system using U.S. Census conversion tables (United States Census Bureau, 2013c). In this paper, the term *NAICS sector* directly referring to a manufacturing sector in the 2007 NAICS classification. In total, 49 154 measured sector-based concentration values for 235 organic chemicals were extracted for the purpose of this paper (see http://pubs.acs.org/doi/suppl/10.1021/acs.est.5b00078). They are considered to be representative of realistic exposures to chemicals in industrial sectors and are independent of any legal threshold. These data were used to determine sets of generic concentrations for each organic chemical/sector couple together with a range of individual data to inform the uncertainty assessment (see below).

Work inspectors (OSHA compliance officers) do not conduct measurements for all chemicals in all industries and generally measure chemicals they consider probable to present a hazard—a choice based on evidence of the chemical's presence and the inspector's experience. A statement on the OSHA-CEHD website supports this hypothesis:

> OSHA compliance officers […] develop a snapshot picture of potentially hazardous chemical exposures and use field evaluation tools to assess their significance: often comparing their measured airborne concentrations of chemicals against established standards. (United States Occupational Health and Safety Agency, 2015).

Building on this, two hypotheses to input generic concentrations in subsectors without measured data were formulated:

Default hypothesis 1 considers that the generic concentration for a chemical/sector couple without measurements is 0, assuming that most sectors with appreciable concentrations have already been covered by work inspection. For couples with measured data, exposure concentrations were extracted at NAICS level 6. Generic concentrations for NAICS levels 5 through 3 were calculated for each chemical with a weighted average of the production worker hours of the NAICS sub-level 6 values.

Conservative hypothesis 2 adopts a more conservative approach for sensitivity study: instead of a null value, generic concentrations at NAICS levels 5 through 3 were allocated based on the weighted average of all available NAICS sub-level 6 production worker hours. Then, from NAICS level 3 down to level 6, sectors without generic concentrations were given the value of their direct upper level sector. A similar generic concentration to immediate neighbour sectors was therefore assumed. For example, if the generic concentration for sector 336123 was missing, the surrogate was the value of sector 33612 or, if also missing, the value of sector 3362 and so on.

Default hypothesis 1 was used as the default method, whereas the second conservative method was used to test the sensitivity to this hypothesis. Further details on both approaches and the filtering criteria used to extract measured concentration data are included in the supporting information (see Table B.1, Figure B.1 in Annex B).

5.2.2.5 Labour hours in U.S. manufacturing industry sectors

Since the method set out in this paper focuses on chemical exposure in industrial manufacturing environments, the labour hour unit is used to measure exposure duration. More specifically, the blue-collar worker hour or production worker hour (referred to in this paper as *labour hour*) was used because these workers are typically more exposed to chemicals than white-collar office workers, as shown in a recent report by the European Foundation for the Improvement of Living and Working Conditions. White-collar worker exposure to chemicals is, on average, lower than that of the average worker, and blue-collar worker exposure is substantially higher than that of the average worker (Parent-Thirion, Fernández Macías, Hurley, & Vermeylen, 2005).

Labour hours were generated using data from the *Annual Survey of Manufactures (United States Census Bureau, 2013a)* and *2007 Census data (United States Census Bureau, 2007):* average labour hours for the 2002–2009 period were available for 233 NAICS level 6 sectors out of 472. Since the correlation between the 2002–2009 average and 2007 dataset was high (R^2=0.994), the missing 139 data were extracted using only the 2007 labour hours from the 2007 Census (United States Census Bureau, 2007). U.S. industrial manufacturing sectors represent some 19 billion labour hours annually. Considering a full time job ($2x10^3$ h/year, 40 h/week), there are 9.5

million full-time blue-collar positions, which is consistent with data from the U.S. Bureau of Labor Statistics (United States Bureau of Labor Statistics, 2013).

5.2.2.6 Uncertainty analysis

A Monte Carlo approach was used to assess uncertainty propagation. But since the measurements do not fit any known distribution and thus cannot be used as an input in the Monte Carlo method, a bootstrap method was used to sample measured concentrations. The bootstrap method randomly resamples data sets to provide a new generic concentration for every iteration and does not rely on any distributional assumptions for the data except for independence and identical distribution (Efron & Tibshirani, 1993). The chemical/sector couples with fewer than three initial measured concentrations were flagged, and this flag was propagated to the upper NAICS levels to identify sectors with potentially high uncertainty. The Monte Carlo approach was used for the other sources of uncertainty: human dose-response (lognormal distribution with a squared geometric standard deviation, GSD^2, of 26.5 for cancer effect and 61.3 for non-cancer effect) and severity factors (lognormal distribution and a GSD^2 of 2.7 for cancer effect and 13 for non-cancer effect) (Huijbregts et al., 2005). At this stage, uncertainty distributions were not associated with inhalation rates or labour hours. The uncertainty was determined for generic concentrations, intakes and CFs at all aggregation levels for all chemical/sector couples using 1 000 resamplings of each original dataset with replacement.

5.2.3 Results

For practical reasons, this section primarily presents results for the seven chemicals associated with the highest impacts. These chemicals are (in alphabetical order): dichloromethane, ethylbenzene, formaldehyde, methyl methacrylate, styrene, tetrachloroethylene and trichloroethylene. Data and results for all chemicals (not limited to the seven presented here) are provided in the supporting information.

5.2.3.1 Organic chemical concentrations

Figure 5.2 illustrates (a) the distribution of ***positive (non-null)*** generic concentrations at NAICS level 6 and (b) the percentage of total industrial sectors labour hours without measurement and those associated with null or positive generic concentration sectors. For each chemical, 50% of the generic concentrations fall within one order of magnitude of the median. Depending on the considered chemical, the 97.5th percentile (represented by the top of the whisker) for chemical-specific data from all sectors exceeds the median by one to two orders of magnitude. The *immediately dangerous for life and health* (IDLH) concentrations are represented by darkened squares. The median of the generic concentrations is two orders of magnitude lower than IDLH concentrations and the maximum within an order of magnitude of the IDLH.

The share of labour hours associated with only null measured concentrations represents 2% to 15% of the total labour hours (Figure 5.2 b). Between 50% of total labour hours for formaldehyde and up to 90% for methyl methacrylate are associated with sectors without measured concentrations. The magnitude of the labour hours share without measured concentrations is explained by the measurement method: since measurement campaigns to estimate potentially dangerous chemicals in the workplace are generally resource extensive, work inspectors tend to focus on sectors and chemicals that are likely to be present and above the limit of detection in these sectors based on experience and on-site information (e.g. industrial process, chemicals use, etc.) (United States Occupational Health and Safety Agency, 2015).

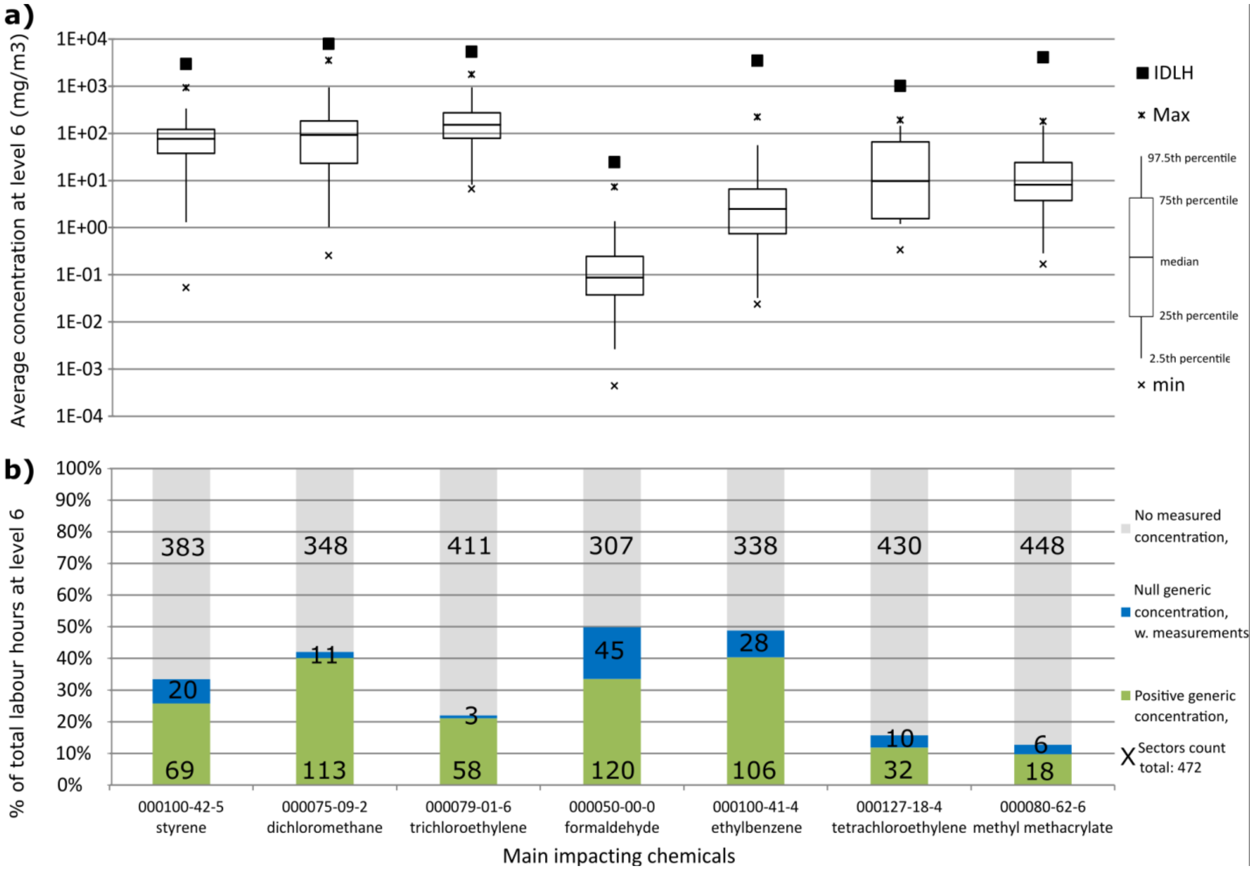


Figure 5.2: a) Distribution of positive NAICS level 6 generic concentrations and b) corresponding labour hour coverage for the seven most impacting chemicals (decreasing order from left to right). *Immediately dangerous for life and health* (IDLH) concentrations are provided for information purpose only.

The distribution of positive measured concentrations at NAICS level 4 and 6 are available for ethylbenzene in Figures B.2 and B.3 in the supporting information (see Annex B).

5.2.3.2 Sector-based intake intensities

Figure 5.3 presents the intakes per labour hour across NAICS level 4 sectors, where the percentage of total labour hours in the sector is on the x-axis and the hourly intake in kg/h (left) and its cumulative representation (right) are on the y-axis. The height of each bar is the intake intensity (kg/h), while the width represents the sector's share of U.S. industry labour hours. Sectors are ranked according to decreasing intake intensity. The resulting area of each bar represents the total intake within each sector. The sum of the area of each bar represents the total intake of chemical *i* across the U.S. manufacturing industry. For the first five chemicals (Figure 5.3 a to e), approximately 80% of the total intake occurs in a limited number of sectors, representing 20% to 30% of total labour hours. For tetrachloroethylene and methyl methacrylate, 95% of the total intake occurs within only 10% of the total labour hours since the number of exposed labour hours is the lowest for these two chemicals (Figure 5.2 b). Sectors with the highest intake intensity mostly correspond to chemical production and metal and plastic product manufacturing (see labels Figure 5.3). The total intake in a sector also depends on the number of hours worked. The sector 3261 *Plastics Product Manufacturing* is the sector with the highest yearly intake of styrene, dichloromethane, trichloroethylene, tetrachloroethylene and methyl methacrylate due to the significant number of hours worked in this sector. A table with Figure 5.3 raw data is included in the supporting information (see SI-all_data.xlsx, http://pubs.acs.org/doi/suppl/10.1021/acs.est.5b00078).

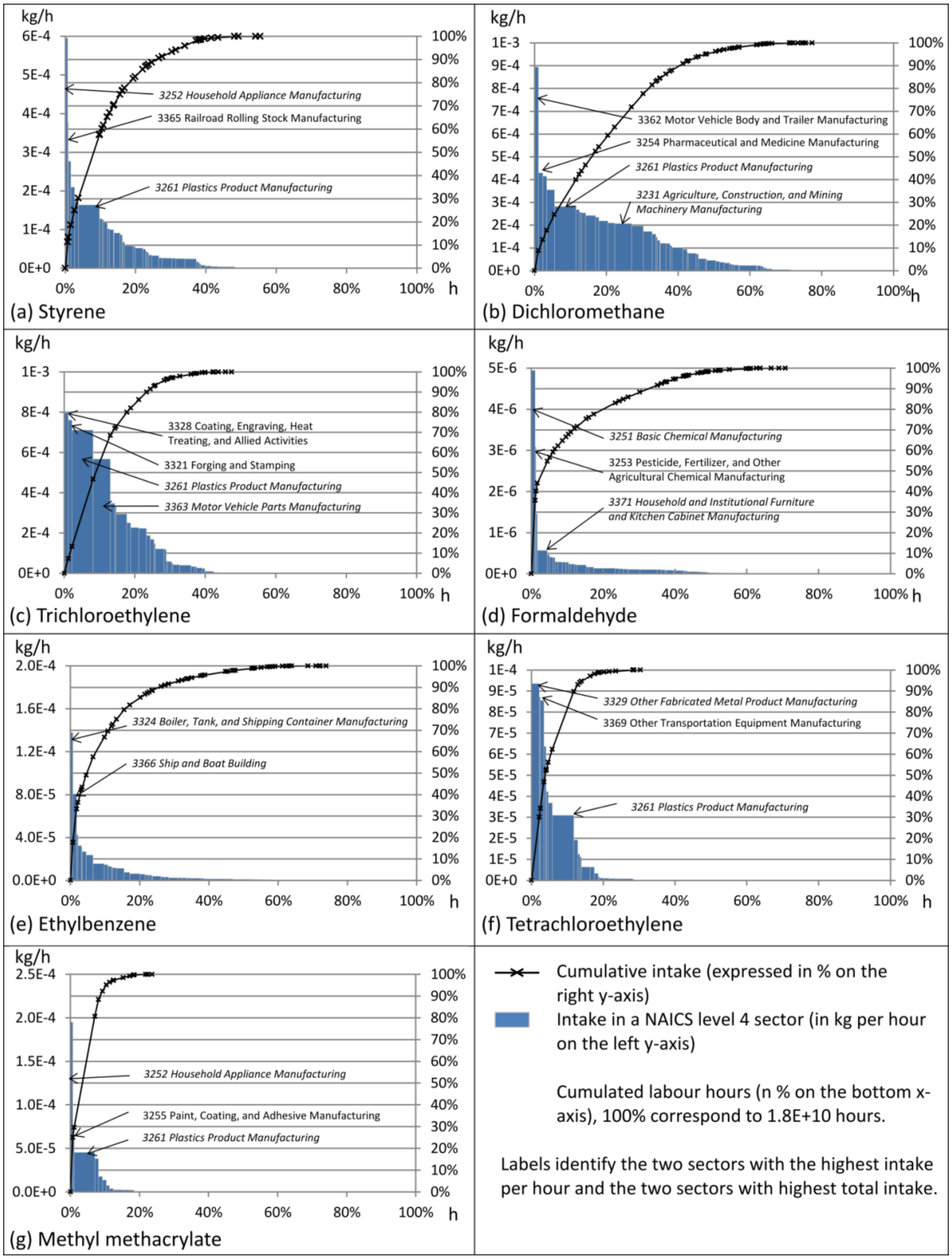


Figure 5.3: Intake per hour of the seven most impacting chemicals (kg/h) as a function of labour hours (h) for each NAICS level 4 sector. The area of each bar represents the total intake in the corresponding sector. Cumulative contribution per sector is represented by the curve on the right y-axis.

5.2.3.3 Sector-based impact intensities per working hour and occupational burden of disease due to chemical exposure

Figure 5.4 plots the potential human health impact in DALY per hour for each sector at NAICS level 4 (y-axis) against the labour hours per sector (x-axis). The height of each bar is the impact intensity (DALY/h, see Equation 5.3), while the width represents the sector's share of U.S. manufacturing industry labour hours. The sectors are ranked according to decreasing impact intensity. The resulting area of each bar depicts the total impact for the sector. The sectors that most contribute to the overall impact show both high impact intensity and a substantial number of labour hours worked. The same figure with sectors ranked by area (i.e. by total impact for the sector) is presented in the supporting information (Figure B.6 in Annex B), and graphs plotting cancer and non-cancer cases separately (without the use of severity factors) are provided in Figures B.4 and B.5 in the supporting information (see Annex B).

The *3261 Plastics Product Manufacturing* sector represents 24% of the overall manufacturing impacts—the highest share among all sectors, though it only has the fifth highest impact intensity (1.66×10^{-4} DALY/h). This is mainly due to its large share of the global labour hours (1.11×10^{9} h or 6% of the total). Despite having the highest impact intensity (4.17×10^{-4} DALY/h), the 3252 *Resin, Synthetic Rubber, and Artificial Synthetic Fibers and Filaments Manufacturing* sector only ranks 20th, contributing 6.8% of the overall impact of the manufacturing sector because of its limited number of labour hours (0.13×10^{9} hours or 0.7% of the total). The contribution of each sector to the overall impacts over the total labour hours is also shown by the cumulative impact contribution curve displayed on the right y-axis, demonstrating that almost 75% of the total impact occurs during 25% of the labour hours in 29 out of the total 86 sectors. Depending on the decision-making context, sectors may be distinguished based on their overall potential burden of disease due to occupational exposure to organic chemicals, varying from 0 DALY to 1.85×10^{5} DALY, or based on their characterization factors or impact intensities, varying from 0 DALY/h to 4.17×10^{-4} DALY/h. Each colour represents the contribution of a single chemical to the sector's impact score. Styrene is the most important contributor, followed by dichloromethane and trichloroethylene. The seven most impacting chemicals are responsible for 91.9% of the total occupational exposure impact of organic chemicals, and the other 228 chemicals represent the remaining 8.1%.

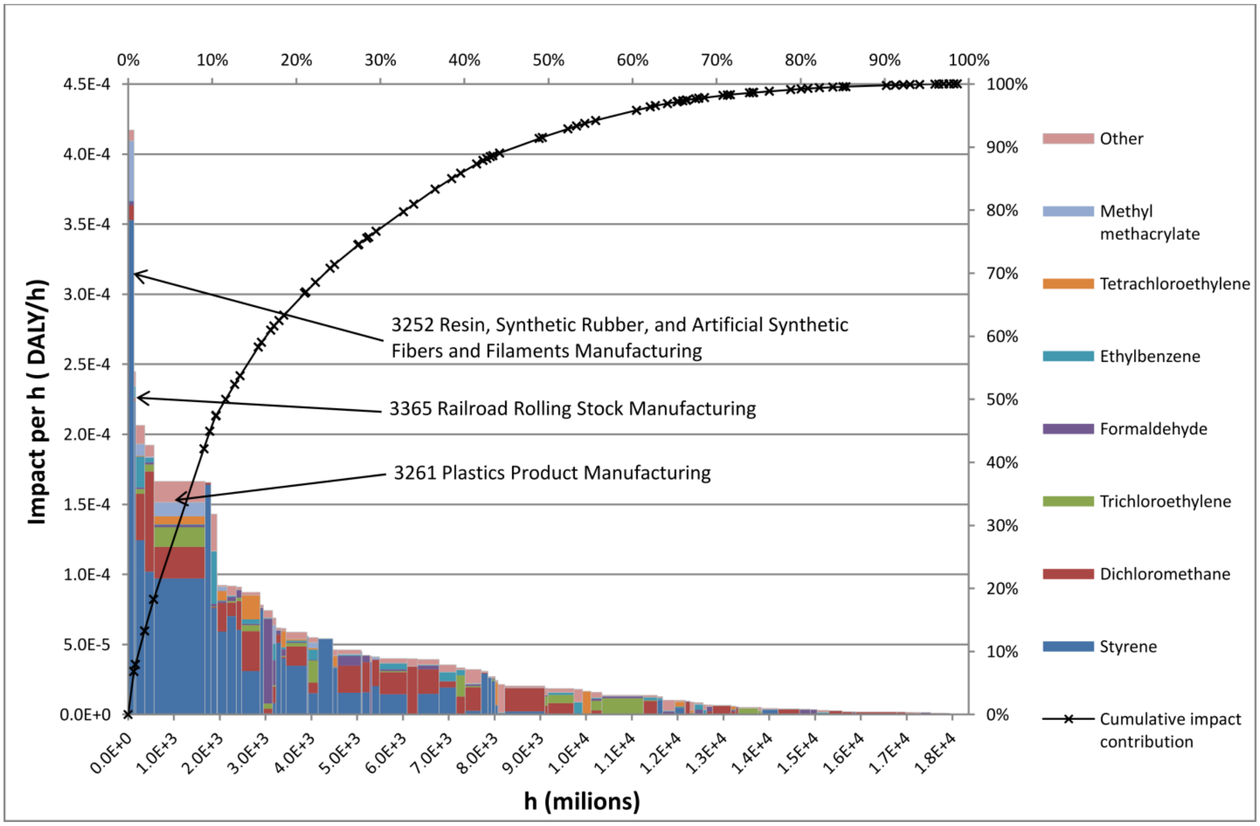


Figure 5.4: Overall occupational human health impacts for the U.S. sectors. Histograms represent potential impacts per sector at NAICS level 4 (according to NAICS nomenclature) as a combination of impact intensity, DALY/hour (left y-axis) and number of labour hours worked in each sector (x-axis). Contribution per chemical within each sector is shown through a color code. Cumulative contribution per sector is shown by the curve on the right y-axis.

The annual total burden of disease due to organic chemicals for blue-collar workers in U.S. industrial manufacturing sectors, which is the sum of the coloured areas of all the histograms inFigure 5.4, is $7.75\text{x}10^5$ DALY (based on default hypothesis 1). As a sensitivity analysis, an upper boundary value ($3.05\text{X}10^6$ DALY) was calculated based on the conservative hypothesis 2. That is less than a factor 5 higher than the main result, which is not substantial as compared to the other sources of uncertainty (see Figure 5.5).

Detailed results for 235 chemicals over 472 NAICS level 6 sectors are provided in the supporting information (see file SI-all_data.xlsx: http://pubs.acs.org/doi/suppl/10.1021/acs.est.5b00078) for 19 069 chemical/sector combinations with measured concentrations. The table includes impact intensities (characterization factors) for cancer and non-cancer (cases/hour and DALY/hour) for which effect factors are available, intake intensities (kg_{intake}/hour), generic concentration (mg/m^3) and labour hours (hours) per sector. Confidence intervals are given for each of these data, and the calculations are detailed below.

5.2.3.4 Uncertainty

Confidence intervals were calculated using a Monte Carlo analysis coupled with a bootstrap approach for the generic concentrations at all NAICS levels and for all indicators throughout the cause-effect chain. Figure 5.5 illustrates the variation in confidence interval estimations associated with each indicator of the cause effect-chain for the total of the entire manufacturing industry and for *3261 Plastics Product Manufacturing,* the sector with the most significant impact.

The uncertainty of the total intakes summed over all manufacturing sectors is restricted, ranging from a factor 1.07 for styrene, which has the highest number of measurements, to 1.31 for tetrachloroethylene with fewer measurements. When considering *3261 Plastics Product Manufacturing*, intake uncertainty ranges moderately increase from a factor 1.13 for styrene up to a factor 2.1 for ethylbenzene, which has the least measurements in the sector. The case-related uncertainty is much more significant than intake uncertainty, ranging from a factor 20 for cancer up to a factor 37 for non-cancer. This is due to the high uncertainty of human dose-response factors (Fantke, Friedrich, & Jolliet, 2012). When calculating the impact expressed in DALY, the severity factor increases the uncertainty to a factor 22 for cancer and 86 for non-cancer. At the impact level, there is little difference between a single sector and the overall manufacturing industries since impact uncertainty is dominated by the effect factor that is common to all. Summing up cancer and non-cancer impacts, the total uncertainty of the human toxicity impact indicator is almost at the same level as the uncertainty of cancer cases, and lower than the uncertainty of the non-cancer impact. This is due to a compensation phenomenon: in summing, high values for certain terms compensate for low values for others.

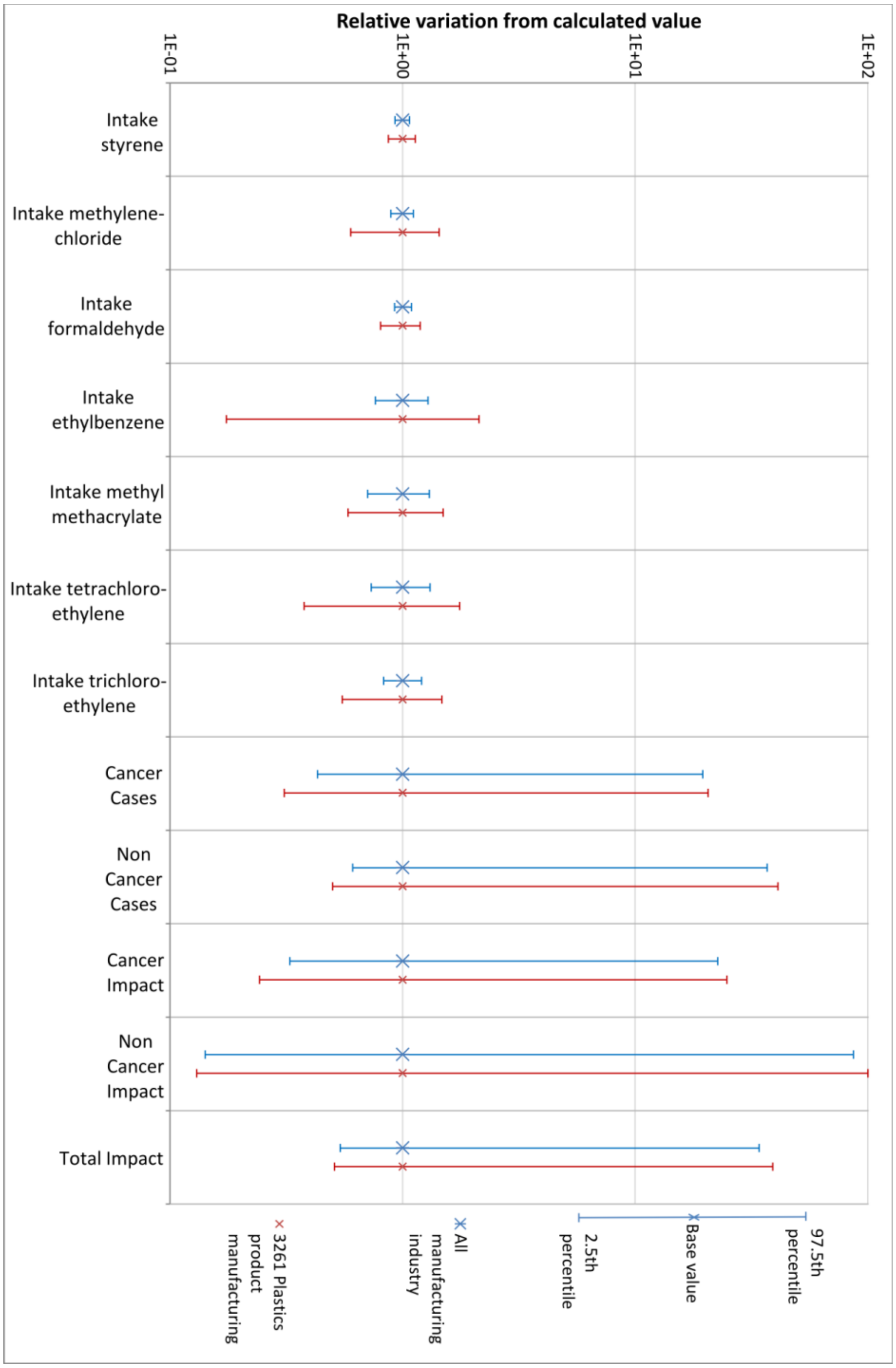


Figure 5.5: Uncertainty propagation along the method's results. The error bars show the 95% confidence interval from the calculated reference value of the indicator labelled on the x-axes.

Detailed figures plotting intake uncertainty for the seven most impacting chemicals are included in the supporting information (see Figures B.7 to B.13 in Annex B).

5.2.4 Discussion

The underlying measured concentrations used to generate sector-specific generic concentrations are coherent with those provided by the International Agency for Research on Cancer (IARC) monographs (World Health Organization & International Agency for Research on Cancer, 2000): most ethylbenzene generic concentrations range from 0.1 mg/m3 to 200 mg/m3, which is consistent with the data presented here (see Figure 5.2, B.2 and B.3 in Annex B). Observed concentrations for styrene, formaldehyde, dichloromethane and tetrachloroethylene are comparable to the concentrations reported in their respective IARC monographs. Trichloroethylene and methyl methacrylate generic concentrations tend to be higher than in the IARC monograph by a factor 4 to 8 (see Table B.2 in Annex B). Generic concentrations of toluene for rotogravure printing sectors (NAICS sectors 323111 and 323117) obtained in this article range between 47.5 mg/m3 and 300 mg/m3 and are comparable with those reported by Walser et al. (2013) The difference is explained by dissimilar time representativeness: 2002–2009 for this paper vs. 1960–1980 for Walser et al. (2013) Finally, an overall potential impact on workers was calculated for the annual activity of the entire industry and amounted to $7.75\text{x}10^5$ DALY. It is comparable to the annual total burden of disease of the PM 2.5 of $1.52\text{x}10^5$ DALY for the North American region (Canada, Cuba, U.S.A.) calculated by Cohen et al. (2004). This macroscopic analysis highlights the seven most impacting chemicals, which account for over 90% of the overall burden. Demou et al. (2011) provided a chemical ranking based on LCA and risk analysis factors, and among the 38 chemicals included in this research, factors were provided for 35 of them. Despite the different objectives, data sources and methods, 5 of the 7 most impacting chemicals in this study are among the 13 chemicals that raise the most concern (LCA ranking), as determined by Demou et al. (2011), the other two having not been assessed (see SI-all_data.xslx: http://pubs.acs.org/doi/suppl/10.1021/acs.est.5b00078).

This new method makes it possible to consistently calculate the potential human health impacts of occupational exposure to organic pollutants by combining chemical concentrations in the workplace and labour hour data. It provides operational LCIA characterization factors with confidence intervals for 19 069 chemical/sector combinations across the entire U.S. manufacturing industry, expressed in DALY per hour worked. Starting from occupational measured concentrations rather than predictions overcomes the limitations of mostly unknown parameters such as dilution volume of the working environment, mixing factor and emission factors across sectors, as required in modeling approaches (Hellweg et al., 2009). When direct measured concentrations collected at the facility are available, they should be used to calculate site-specific CFs, overriding the sector-default CFs developed in this paper.

To make this novel approach operational, a clear practical interface between life cycle inventory and impact assessment steps was redefined. Instead of linking pollutant concentrations to the functional unit as suggested by Hellweg et al. (2009), the method links labour hours worked in sector j per functional unit as the default inventory flows, which are then linked to the observed concentration-based CFs (DALY/h_j) developed in this paper. While labour hours per functional unit may be directly collected for foreground core processes, the contribution to occupational exposure from the supply chain (i.e. tier 1, 2, 3, etc.–so called background processes) may be dominant and also need to be integrated. For these background processes, the Leontief input-output approach (Leontief, 1986), which calculates the monetary output of each sector of the national economy for a given demand, may be used to determine the labour hours worked in each industrial sector for a given demand (Benoit-Norris et al., 2012; Norris, Norris, & Aulisio, 2014). By combining these labour hours with the impact intensities determined in this paper, it becomes possible to calculate cumulative occupational impacts for all background processes in the supply chain. Once the hours worked per FU in each sector are obtained, the characterization factor given for the entire manufacturing industry in this paper can easily be used to determine the life cycle occupational health impact per FU. Figure B.14 in the supporting information (see Figure B.14 in Annex B) provides an illustrative example of such a calculation, showing the importance to consider the occupational impacts over the entire manufacturing industry, since the supply chain occupational impacts may exceed the direct impacts in the producer manufacturing sector.

The new method is applicable to all types of pollutants, as long as effect factors were specifically determined. This paper focused on organic chemicals and provides intake intensities and characterization factors for all organics for which an effect factor is available in the USEtox database (Rosenbaum, R. et al., 2008). The operational approach developed for organic chemicals may be further expanded to include exposure data for dust, particles and inorganic matter.

The sets of generic concentrations and sector-based labour hours developed in this article are only valid in the U.S. context and represent a “snapshot picture of potentially hazardous chemical exposures” (United States Occupational Health and Safety Agency, 2015). Further work is required to evaluate and enhance the representativeness of these U.S.-focused generic concentration sets with respect to realistic usual exposures through the addition of other available measured concentration databases such as the Integrated Management Information System database (IMIS), as suggested by Lavoue, Friesen et Burstyn (2013), and explicitly consider the use of protective equipment. Gathering occupational concentrations in other countries and eventually defining an extrapolation method to estimate data for emerging countries with less monitored data is key in order to use the approach on a global scale and combine it with working hours inventories derived at global levels (Alsamawi, Murray, & Lenzen, 2014).

The uncertainty analysis showed that the uncertainty is dominated by the effect factor and that aggregating the data to obtain impact intensities in cases or in DALY per hour substantially increases the uncertainty due to the high uncertainty of the human dose response factors and severity factors, respectively. Thus, the results must be interpreted at the intake and impact levels.

In addition to LCA applications, the creation of a systematic set characterizing ranges and frequencies in observed concentrations and intakes over hours worked for 472 industrial sectors and 235 chemicals constitutes an important input to characterize the occupational exposome – the inventory of “every exposure to which an individual is subjected from conception to death” as defined by Wild, Christopher Paul (2012) - of the general U.S. population for the 2002–2009 period. It would be of interest to further harness the entire OSHA database over the 1984–2013 period in order to be able to provide exposure ranges across the entire U.S. working population, associating and comparing the estimated individual exposures to the National Health and Nutrition Examination Survey (NHANES) individual biomarker results and related occupational survey data (Centers for Disease Control and Prevention (CDC), 2014).

CHAPITRE 6: ARTICLE 3: OCCUPATIONAL HEALTH IMPACTS DUE TO EXPOSURE TO ORGANIC CHEMICALS OVER AN ENTIRE PRODUCT LIFE CYCLE

6.1 Présentation de l’article

Cet article, publié le 6 Décembre 2016 dans le journal *Environmental Science and Technology* présente les travaux de recherche effectués en réponse au deuxième objectif du projet de recherche.

Cet article présente une méthodologie permettant de calculer, pour l’ensemble d’une chaîne de valeur, les impacts potentiels sur la santé des travailleurs en couplant les facteurs de caractérisation développés au Chapitre 5 avec un inventaire des heures travaillées dans chaque secteur industriel.

Les informations supplémentaires soumises avec l’article sont disponibles dans l’annexe C et aux adresses suivantes : http://pubs.acs.org/doi/abs/10.1021/acs.est.6b04434 et https://github.com/gaelkijko/occ_expo_lca.

Auteurs : Gaël Kijko, Olivier Jolliet, Manuele Margni.

6.2 Manuscrit

6.2.1 Introduction

Life cycle assessment (LCA) aims to provide decision makers with meaningful information on the potential environmental impacts of different product systems in a life cycle perspective (Hauschild, Michael Z., 2005) with the aim to avoid impact shifting from one activity to another or from one life cycle stage to another (European Commission Institute for Environment and Sustainability - Joint Research Center, 2010a). Human health (HH) impact is among the indicators considered in life cycle impact assessment (LCIA) (European Commission Institute for Environment and Sustainability - Joint Research Center, 2010a), with a primary focus on assessing the potential impacts associated with chemicals or particulate matter emitted outdoors (Fantke et al., 2012; Gronlund, Humbert, Shaked, O'Neill, & Jolliet, 2015; Humbert et al., 2011).

Despite recent research efforts to integrate the occupational environment into the LCIA framework (Antonsson & Carlsson, 1995; Demou et al., 2009; Hellweg et al., 2005; Hofstetter & Norris, 2003; Kim & Hur, 2009; Scanlon et al., 2014; Schmidt, A. et al., 2004), current LCA studies have paid little attention to occupational exposure. Nevertheless, there is growing interest in LCIA to better account for the potentially high near-field exposures to chemicals emitted in the direct vicinity of the exposed population (Jolliet, Ernstoff, Csiszar, & Fantke, 2015). Efforts to develop methods integrating near-field exposures in LCA have been based on developing LCA-adapted indoor compartmental models to assess the impacts of exposure to chemicals based on indoor emission data during the production phase (Demou et al., 2009; Golsteijn et al., 2014; Hellweg et al., 2009; Kikuchi, Yasunori & Hirao, 2008; Tong, Zhai, & Li, 2015; Walser et al., 2013; Walser et al., 2015) and the product use (e.g. during cooking (Rosenbaum, R. K. et al., 2015), for wood products (Chaudhary & Hellweg, 2014)). Other methods quantify the dermally-mediated impacts of chemicals in personal care products (Ernstoff et al., 2016; Safford et al., 2015). Recently, the USEtox model, a scientific consensus model used for characterizing environmental dispersion and impact of chemicals (Rosenbaum, R. et al., 2008), published its 2.0 version including a one-box indoor model for near-field including household and occupational settings.

However, intake fraction predictions and emission-based impact modeling in occupational settings remain a challenge to perform over multiple industry sectors since a) workplace chemical emissions during the manufacturing stage of a product are not always known or the data are not publicly available as are the characteristics of the emission location; b) impacts will occur throughout the entire manufacturing supply chain (unlike use phase near-field exposures, which are often clearly delineated for the LCA of a given product) and c) worker populations vary by industry, worksite and workplace practice. In the absence of a way to systematically apply these methods in LCA, another operational method must be developed to cover the entire supply chain.

In addition to emissions-based impact modeling in occupational environments, other methods developed to address occupational health in LCA can be classified into two categories. The first one includes methods that use reported fatal and nonfatal occupational injury and illness data to calculate generic characterization factors for each economic sector (Antonsson & Carlsson, 1995; Hofstetter & Norris, 2003; Kim & Hur, 2009; Pettersen & Hertwich, 2008; Scanlon et al., 2013;

Scanlon et al., 2014; Schmidt, A. et al., 2004). These methods are limited by the data: nonfatal injury and illness data are contingent on both declaration and acknowledgement and therefore induce a significant risk of undercounting (Hofstetter & Norris, 2003). Moreover, these methods do not provide chemical-specific characterization factors, but only aggregated sector-specific industry values for all reported injuries and illnesses. The second category regroups methods combining measured occupational concentrations and the number of hours worked in the environment to directly determine intake, thus overcoming the need to gather sector-specific emissions parameters (Hellweg et al., 2009). Several articles in the occupational health and safety and LCIA fields use this method, which generally focuses on a single process or industry (Collinge et al., 2013; Kauppinen et al., 2006; Kikuchi, Yasunori & Hirao, 2008; Walser et al., 2013; Witter et al., 2014). Relying on measured occupational concentrations in the workplace, Kijko et al. proposed a method that provides, for each U.S. industrial sector, the chemical-specific impacts per blue collar worker hour (BCWH) in the sector (Kijko, Gaël et al., 2015). Blue collar workers are "manual industrial workers" while white collar workers that are "persons whose job is professional or clerical and usually salaried" (Collins, 2015b). The characterization factors (in DALY/BCWH), or hour-based impact intensities, developed by Kijko *et al.* account for 235 organic chemicals and their occupational impacts in a given manufacturing sector. However, supply chain occupational impacts attributable to chemical exposures across the product life cycle are not yet characterized. In this article, occupational impacts due to exposure to organic chemicals occurring at the manufacturing facility producing a given product or commodity are considered to be generated by emissions occurring in the sector itself, while supply chain impacts are generated by the activities along the supply chains upstream the manufacturing sector (i.e. all activities of the product supply chain excluding the manufacturing facility). To calculate these supply chain impacts for a given product, the inventory of BCWH worked in each sector per considered functional unit (FU) must first be determined. Major life cycle inventory databases such as Ecoinvent (Frischknecht, 2005) are based on physical amounts and do not provide the number of hours worked. Input-Output (I-O) databases use currencies as base units (Suh, S., 2004) but could be extended to calculate hours worked in an industry supply chain. Social LCA, and working hours have, for example, been considered and integrated into the Social Hotspot Database (Benoit-Norris et al., 2012). Labor hours (calculated using IO model) have been used to calculate to characterize international labor and wage flows (Alsamawi et al., 2014). This research uses BCWH worked across the entire supply chain to inform both the inventory in LCA and the calculation of impacts per hour worked.

This article aims to expand the scope of previous studies, in particular Kijko, Gaël et al. (2015) and make it possible to characterize potential human health impacts attributable to occupational exposures to chemicals across the entire supply chain. More specifically, we aim to: (a) develop an approach to compute BCWH worked throughout the supply chain per functional unit; (b) provide recommendations to account for available measured data and generic data generated with IO for the supply chain; (b) illustrate the application of the approach in an LCA case study that integrates human health impacts from occupational exposure to organic chemicals throughout the entire life cycle and compares them to other sources of human health impacts; and (d) calculate and compare manufacturing facility and supply chain occupational impacts of organic chemicals per US dollars for each commodity manufactured in the US;.

6.2.2 Methodology

By convention, in the following equations, characters with an upper arrow represent vectors and bold characters represent matrices. The notation $\hat{g}$ correspond to the diagonal matrix based on vector $\vec{g}$. Roman characters represent scalars. The $ symbol refers to US dollars. DALY is a unit developed by Murray, C. J. (1994) that serves to compare human health impacts that would be impractical to compare otherwise (such as cancer and non-cancer impacts). For practical reasons, in this paper we only provide aggregated results (cancer DALY and non-cancer DALY). Characterization factors (CF) for cancer cases, non-cancer cases and aggregated DALY are provided in supporting information.

(see SI.xlsx: http://pubs.acs.org/doi/suppl/10.1021/acs.est.6b04434)

6.2.2.1 Expanding the framework: worker health impacts over the entire supply chain

The starting point for this paper is the framework developed by Kijko, Gaël et al. (2015), where human health impact for effect e due to occupational exposure to chemical c in sector s (D_{ecs}, in DALY/FU) is calculated as the product of the characterization factor per BCWH worked, for effect e (carcinogens or non-carcinogen) due to exposure to chemical c in sector s (CF_{ecs}, in

DALY/h in the North American Industry Classification System – NAICS (United States Census Bureau, 2013b)) and the number of hours worked in this sector s (h_s, h):

$$D_{ecs} = CF_{ecs} \times h_s \tag{6.1}$$

The CF_{ecs} and corresponding uncertainty ranges were calculated based on measured occupational concentrations from the US Department of Labor Occupational Safety and Health Administration (OSHA), which covers 235 chemicals in 430 industrial sectors. The total potential impact in the US manufacturing industry amounts to 775 000 DALY. The global burden of disease (GBD) evaluates many risk factors including occupational risks ("Institute for Health Metrics and Evaluation (IHME). GBD Compare," 2015; Murray, C. J. L. et al., 2012). When excluding potential cancer impacts from styrene, tetrachloroethylene and trichloroethylene to be coherent with the GBD methodology, the total potential impact in the US manufacturing industry due to exposure to organic chemicals is 300 000 DALY with 3 376 DALY attributed to occupational exposure to benzene. The 2005 GBD evaluates the impact of occupational exposure to benzene at 5 762 DALY and occupational exposure to all carcinogens at 397 000 DALY ("Institute for Health Metrics and Evaluation (IHME). GBD Compare," 2015). For a more detailed analysis of the characterization factors for manufacturing facility exposures, refer to Kijko, Gaël et al. (2015).

We now extend this framework to calculate the BCWH worked in each sector over the entire supply chain including the manufacturing sector. Based on Leontief's work, the IO analysis is widely used in LCIA to model the supply chain (Chang, Ries, & Wang, 2010; Lave, 1995; Matthews & Small, 2000) (e.g. CEDA model (Suh, S., 2004)) or coupled with process modeling in hybrid methods (Suh, Sangwon et al., 2004), yielding the total commodity production needed (vector $\vec{X}$**, in** \$/FU, in the IO tables classification) (United States Bureau of Economic Analysis, 2014).

$$\vec{X} = (\boldsymbol{I} - \boldsymbol{A})^{-1} \times \vec{Y} \tag{6.2}$$

The vector $\vec{X}$ may be calculated as the product of $(\boldsymbol{I} - \boldsymbol{A})^{-1}$ and $\vec{Y}$, as per the IO framework(Leontief, 1986). $(\boldsymbol{I} - \boldsymbol{A})^{-1}$ is composed of columns representing the total commodity production needed to produce one dollar of value of the column commodity (\$/\$ in IO classification). $\vec{Y}$ is the final demand vector per FU at the manufacturing stage ($/FU in IO classification).

The total commodity production may be combined with an intervention matrix $\boldsymbol{B}$: a matrix providing the dollar-based work intensity (number of BCWH worked in each industry, NAICS classification) per $ of commodity-specific production values (IO classification) to obtain the total BCWH worked in each NAICS sector.

$$\vec{h} = \boldsymbol{B} \times \vec{Y} \tag{6.3}$$

By combining Equation 6.3 with Equation 6.1 and 6.2, for final demand $\vec{Y}$, we obtain the impact for effect e due to the occupational exposure of workers to chemical c over the entire supply chain of commodity, including the manufacturing sector (D_{ec}, in DALY/FU):

$$D_{ec} = \overrightarrow{CF}_{ec} \times \vec{h} = \overrightarrow{CF}_{ec} \times \boldsymbol{B} \times \vec{X} = \overrightarrow{CF}_{ec} \times \boldsymbol{B} \times (\boldsymbol{I} - \boldsymbol{A})^{-1} \times \vec{Y} = \overrightarrow{CF2}_{ec} \times \vec{Y} \tag{6.4}$$

Where $\overrightarrow{CF2}_{ec}$is the vector of characterization factor for each IO commodity (in DALY/$ or cases/$) provided in supporting information (see SI.txt for the detailed factors by chemical-commodity couple or SI.xlsx for the aggregated factors by IO sector: http://pubs.acs.org/doi/suppl/10.1021/acs.est.6b04434). A method to calculate the impact in each IO commodity or NAICS sector is described in supporting information (see Equation S1 to S16 in SI.1 and SI.2. in Annex C).

To build the $\boldsymbol{B}$ matrix, we started with a binary matrix $\boldsymbol{CONV}$ of elements $conv_{ij}$ mapping the BCWH from the NAICS classification (as rows, m sectors) into the IO classification (as columns, n sectors) using conversion data from the US Bureau of Economic Analysis(Stewart, Stone, & Streitwieser, 2007). Seeing as several NAICS sectors must be mapped to multiple IO sectors due to different definitions of sector boundaries, BCWH were proportionally split to the total production ($, class_IO) of the IO sectors to which they are mapped. We obtained a normalized conversion matrix $\boldsymbol{CONV_{norm}}$ of elements $conv_{norm_{ij}}$:

$$conv_{norm_{ij}} = \frac{conv_{ij} \times g_j}{\sum_{k=1}^{m} (conv_{ik} \times g_k)} \tag{6.5}$$

g_j is the total production of the IO sector j ($).

Then, using the same industry as technology construct used in the CEDA IO model(Suh, S., 2004) we convert the IO sectors into IO commodities:

$$\boldsymbol{B} = \widehat{BCWH} \times \boldsymbol{CONV_{norm}} \times \widehat{g^{-1}} \times \boldsymbol{V} \times \widehat{q^{-1}} \qquad (6.6)$$

With $\widehat{g^{-1}}$ the diagonal matrix of the inverse of IO primary industry total output (1/\$). $\boldsymbol{V}$ is the make matrix with IO sectors as rows and IO commodities as columns. Each element v_{ij}provides the total output of commodity j per sector i. $\widehat{q^{-1}}$ is the diagonal matrix based on the inverse of total primary commodity output (1/\$).

The structure of the $\boldsymbol{B}$ matrix is further detailed in Table C.1 (see Annex C).

6.2.2.2 Manufacturing facility and supply chain organic chemical impact on workers in the US economy

We applied the new extended framework to assess occupational exposure throughout the entire supply chain of all commodities produced in the US economy. We calculated manufacturing facility and supply chain dollar based impact intensities and labor intensities for the 430 commodity categories, using final demand \$. Based on these data, we calculated, for each sector, health impacts for both the manufacturing facility (i.e. where the commodity is produced or assembled) and the supply chain (i.e. the all activities upstream the manufacturing facility, excluding the facility itself). For the purpose of this application, we used the 19 069 characterization factors provided in Kijko, Gaël et al. (2015) for exposure to organic chemicals in each of the 472 individual industrial sectors of the 2007 U.S. North American Industry Classification System (NAICS). The U.S. Annual Survey of Manufacture (ASM) (United States Census Bureau, 2013a) (years 2002–2006 and 2008–2009) and the five-year economic census (United States Census Bureau, 2007) (year 2007) provided the BCWH worked in the NAICS classification. The 2002–2009 employment data are used for coherence with the CF_{ecs} that were calculated based on measured 2002–2009 occupational concentration databases. This adds up to 18.6 billion BCWH worked annually in the US, approximately corresponding to 9.3 billion full-time blue-collar workers, which is consistent with employment data from the Bureau of Labor Statistics for the same period. The IO model is based on the CEDA 4.6 model (Suh, S., 2004), which relies on the 2002 Benchmark IO Accounts with 430 individual commodity categories. It provides $\vec{q}$ the total primary commodity output (in US \$) and final demand for the U.S. economy for each IO commodity. The US Bureau of Economic Analysis (BEA) provides $\boldsymbol{V}$ the make matrix and $\vec{g}$, the total primary industry output (United States Bureau of Economic Analysis, 2014).

The mapping from the IO to the NAICS 2002 classification comes from the U.S. Bureau of Economic Analysis (Stewart et al., 2007).

Further details on the basis of conversion matrix Q for the U.S. economy may be found in file SI.xlsx (see http://pubs.acs.org/doi/suppl/10.1021/acs.est.6b04434). A summarizing figure providing data source for each portion of the damage calculation is provided in supporting information (Figure C.1, see Annex C).

6.2.2.3 Case study

The approach developed in this article was then applied to evaluate the occupational health impacts of an office lounge seat with a FU defined as *the use of an office lounge seat for 5 years in an office environment*. Manufacturing facility health impacts were calculated based on actual measurements at the production facility of the chair manufacturer performed by an independent contractor for worker exposure monitoring purpose. Supply chain health impacts are added based on the approach described in the methodology section, relying on sector average concentrations. Health impacts from user exposure during the use phase are also added. The general population refers to the global human population exposed to outdoor emissions, excluding the user exposure to emissions during use phase that are considered separately.

An office lounge seat is a piece of furniture designed for break rooms and informal meeting rooms. It is made of fabric, wood, foam and a metallic frame. Data on material and energy purchases, occupational exposure concentrations to chemicals and BCWH worked at the manufacturing plant correspond to empirical data measured and provided by an undisclosed industrial partner. All activities across the product value chain are assumed to occur in conditions similar to those of US manufacturing. Purchase value per FU is provided at the sector level (see Table C.2 in Annex C). According to the non-disclosure agreement, all other data on the product are made available at a high aggregation level. The end-of-life scenario considers one third of the product going to landfill, one third to municipal incineration and one third to recycling plants. Emissions during the use phase are modeled according to a first order decay model (Guo, 2002a, 2002b). All other use phase parameters, such as use period, were provided by the manufacturer.

The potential human health impacts associated with the office lounge seat includes: (i) the occupational impacts due to worker exposure to organic chemicals at the manufacturing plant (calculated with occupational exposure concentration data, BCWH worked by FU provided by the industrial partner and the effect factors (EF) from USEtox (Rosenbaum, Ralph K. et al., 2011)), (ii) the supply chain occupational impacts due to worker exposure to organic chemicals calculated along the entire supply chain, (iii) the exposure of users to organic chemical emissions from the office lounge seat over the five-year use phase (assuming one box model environment with room volume of $120m^3$, ventilation exchange rate of $1h^{-1}$ and mixing factor of 0.9 as per Hellweg et al.(Hellweg et al., 2009) and a first order decay (Guo, 2002a, 2002b) model extrapolated from two measurements from a $1m^3$ chamber at 23˚C at 3 and 7 days), and (iv) the exposure of the general population to outdoor life cycle organic chemicals associated with the supply chain, manufacturing process and end-of-life (using SimaPro 8.0.4.30, ecoinvent database v2.2 and the Impact 2002+ LCIA method limited to carcinogens and non-carcinogens).

All calculated factors are provided with confidence intervals calculated with a Monte Carlo analysis considering the uncertainty on the CF from Kijko, Gaël et al. (2015) and on the effect factors from the USEtox model (Rosenbaum, R. et al., 2008). These uncertainty factors were estimated based on the intra-sectoral variability of measured occupational concentrations and therefore reflect the existence of different production methods or company practices. In the case study, the uncertainty of the general population’s exposure was determined using the Monte Carlo analysis tool included in the SimaPro software.

6.2.3 Results

6.2.3.1 Supply chain worker health impacts due to exposure to organic chemicals in the US economy

6.2.3.1.1 Inventory generation: blue collar hours worked

Figure 6.1 presents the distribution of the dollar-based work intensity for the production of each IO commodity (in BCWH per $ of commodity). Each bar represents an IO commodity, with its width corresponding to the total annual production value and its height corresponding to its dollar-based work intensity. The area of each bar from the product of dollar-based work intensity and total annual production volume represents the total BCWH worked producing each IO commodity. The dot above each column shows the total dollar-based work intensity of the commodity (BCWH worked in this commodity producing sector and its supply chain per million $ of production). The most work-intensive commodities, such as *315210-Cut and sew apparel contractors*, require over $2.5\text{x}10^{+4}$ BCWH worked per million $ of total annual production—two orders of magnitude greater than the least intensive, such as *324110-Petroleum refineries*, with a total of $4.6\text{x}10^{+2}$ BCWH worked per million $ of total annual production. Commodity *336300-Motor vehicle parts manufacturing* has the highest number of BCWH worked (highest area in the graph) due to its high final demand. The median dollar-based work intensity across the 279 manufacturing sector commodities of the economy is $5.9\text{x}10^{+3}$ BCWH worked per million $ of total annual production.

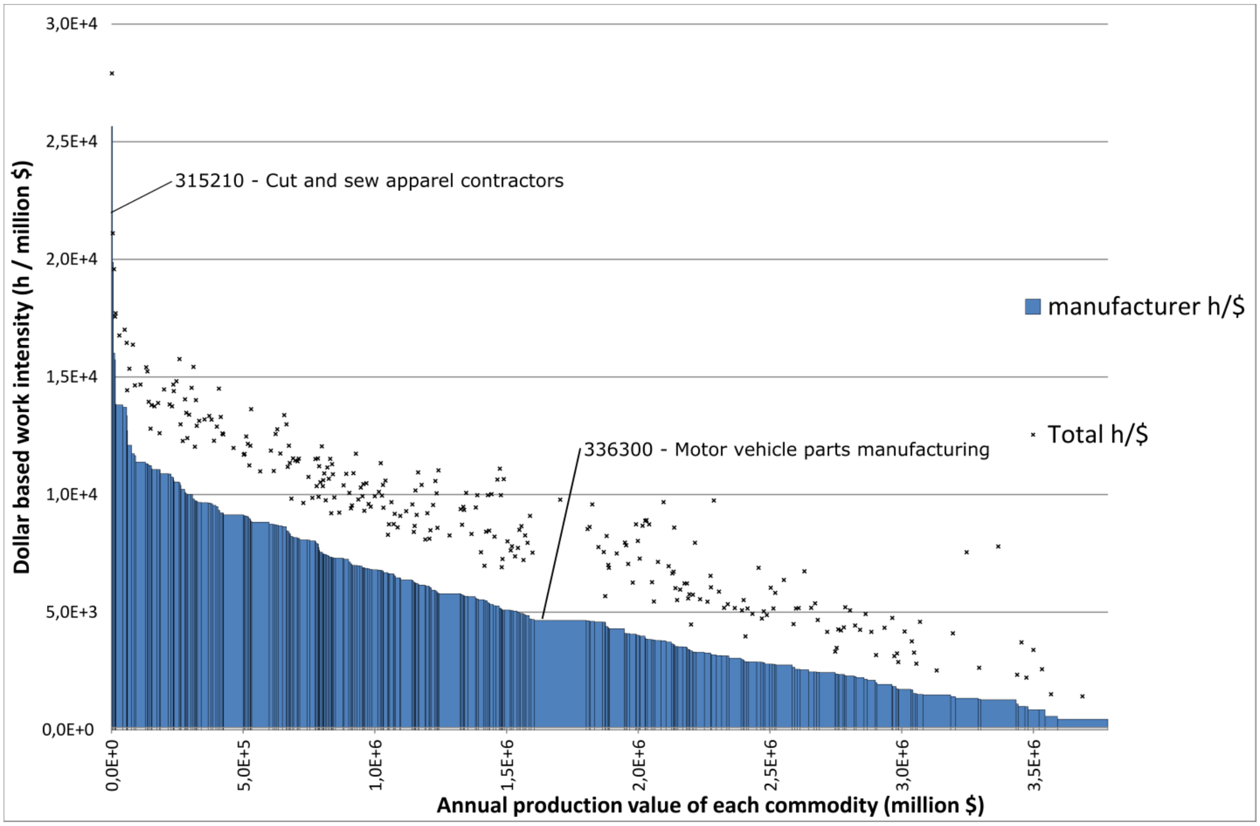


Figure 6.1: Blue collar worker hours (BCWH) worked producing each IO commodities: area represented by the product of dollar-based work intensity (hours worked per million $ of industrial commodity in its manufacturing sector (y-axis) multiplied by the annual production value ($) for the 279 manufacturing sector commodities of the economy. Total h/$ includes manufacturer hours worked and supply chain hours.

We provide the manufacturing facility and total (manufacturing facility and supply chain) inventory factors matrices with the manufacturing facility and total amounts of BCWH in each industrial NAICS sector per production $ of each IO commodity (see supporting information worksheets Total_hours_inventory and Q matrix in file SI.xlsx).

6.2.3.1.2 Impact assessment: impact per $ final demand

Figure 6.2 presents the potential impacts due to occupational exposure to organic chemicals in DALY per $ final demand of each IO commodity (y-axis) for all industrial commodities of the

U.S. economy against the final national consumption for each commodity (x-axis). Each bar height corresponds to the total dollar-based potential impact intensity of the corresponding commodity production including the supply chain. Each bar area is proportional to the total impact due to the production of the corresponding commodity including the supply chain. The assessed impacts include both impacts for workers in the considered commodity manufacturing facility (blue) and supply chain impacts (green). If plotted against the total production, this would lead to double counting since part of the production of each commodity is used in other commodity supply chains (thus included in their supply chain impact).

Total dollar based impact intensity (including both manufacturing facility and supply chain impacts) vary by about two orders of magnitude across commodities with the highest values for sector *332420- Metal tank (heavy gauge) manufacturing* at 3.8 DALY/million $, followed by *336612-Boat building* at 3.5 DALY/million $. For the commodities with the highest dollar-based impact intensity, impacts are mainly due to occupational exposure during the considered commodity production. For these two commodities, the main impacting chemicals are, in decreasing impact order, styrene, ethylbenzene, ethylene glycol monobutyl ether, xylene and toluene for *332420 – Metal tank (heavy gauge) manufacturing* and styrene, methylene chloride, methyl-methacrylate, trichloroethylene and ethylbenzene for *336612 – Boat building*. The chemicals, with the exception of ethylene glycol, monobutyl ether, are among the seven most impacting chemicals in the US industry, as identified in Kijko et al. 2015. The high occupational dollar-based impact intensity commodities correspond to commodities with both a high number of hours worked per $ final demand and high total DALY per hour worked. No correlation was found between the total dollar-based impact intensity and the dollar-based labor intensity: the high impact per $ is related to commodities with both high dollar-based labor intensity and high dollar base impact intensity (see Figure C.2, in annex C).

The lower the dollar-based impact intensity, the lower the relative contribution from the producing sector. Certain impacts are as low as $1x10^{-2}$ DALY/million $, essentially due to occupational exposure in the supply chain (green color). The red color represents the potential impact due to the production of the same commodity from upstream demand in the supply chain, which is negligible. The rest of the commodities have even lower impacts per $, entirely due to the supply chain (see Figure C.3, a similar figure including all commodities in supporting information). The impacts of the 279 commodities plotted in Figure 6.2 add up to 2/3 of the total impact due to exposure to organic chemicals in all US manufacturing sectors.

Commodity *336112 – Light truck and utility vehicle manufacturing* and *230201 – Residential permanent site single- and multi-family structures* show the highest absolute impacts expressed in total DALY with 4.42x10^{+4} DALY/year and 4.24x10^{+4} DALY/year, respectively (largest areas on the graphs), due to high final demand for these commodities combined with medium impacts per $.

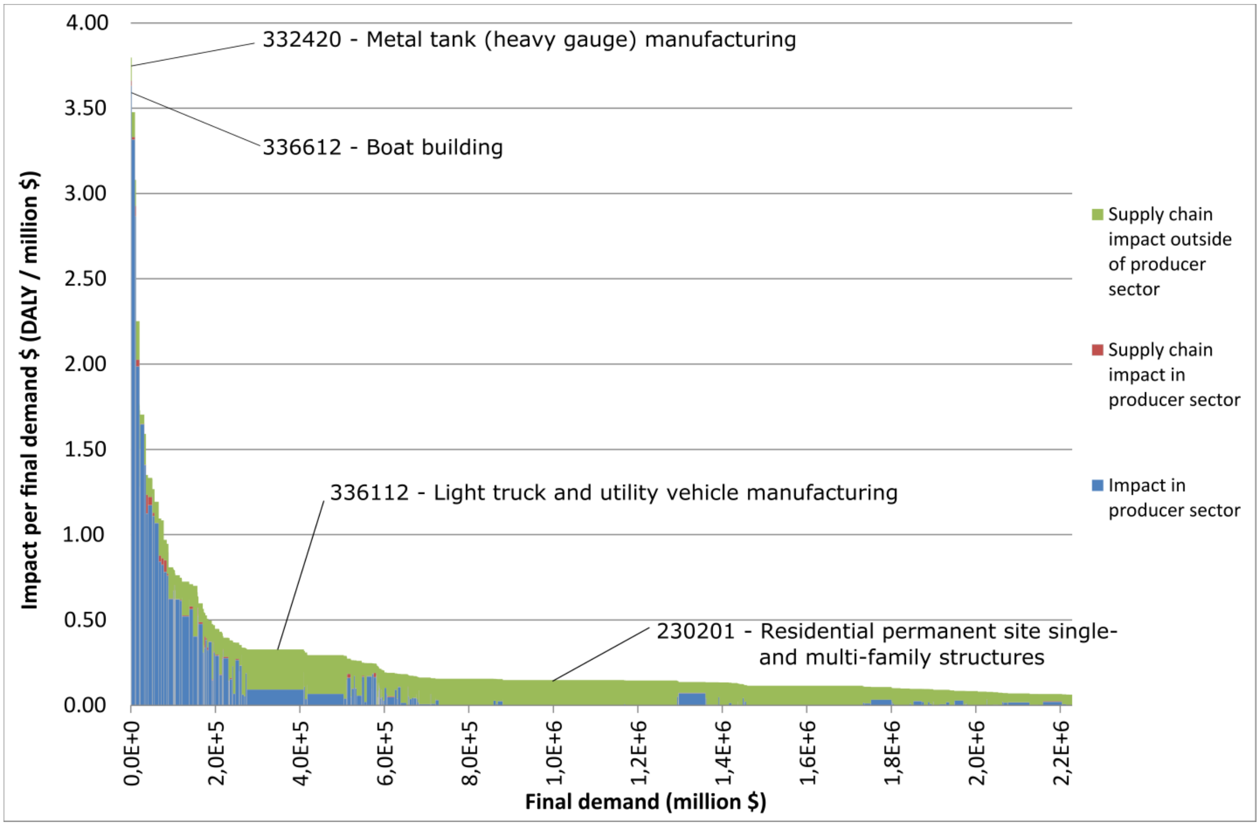


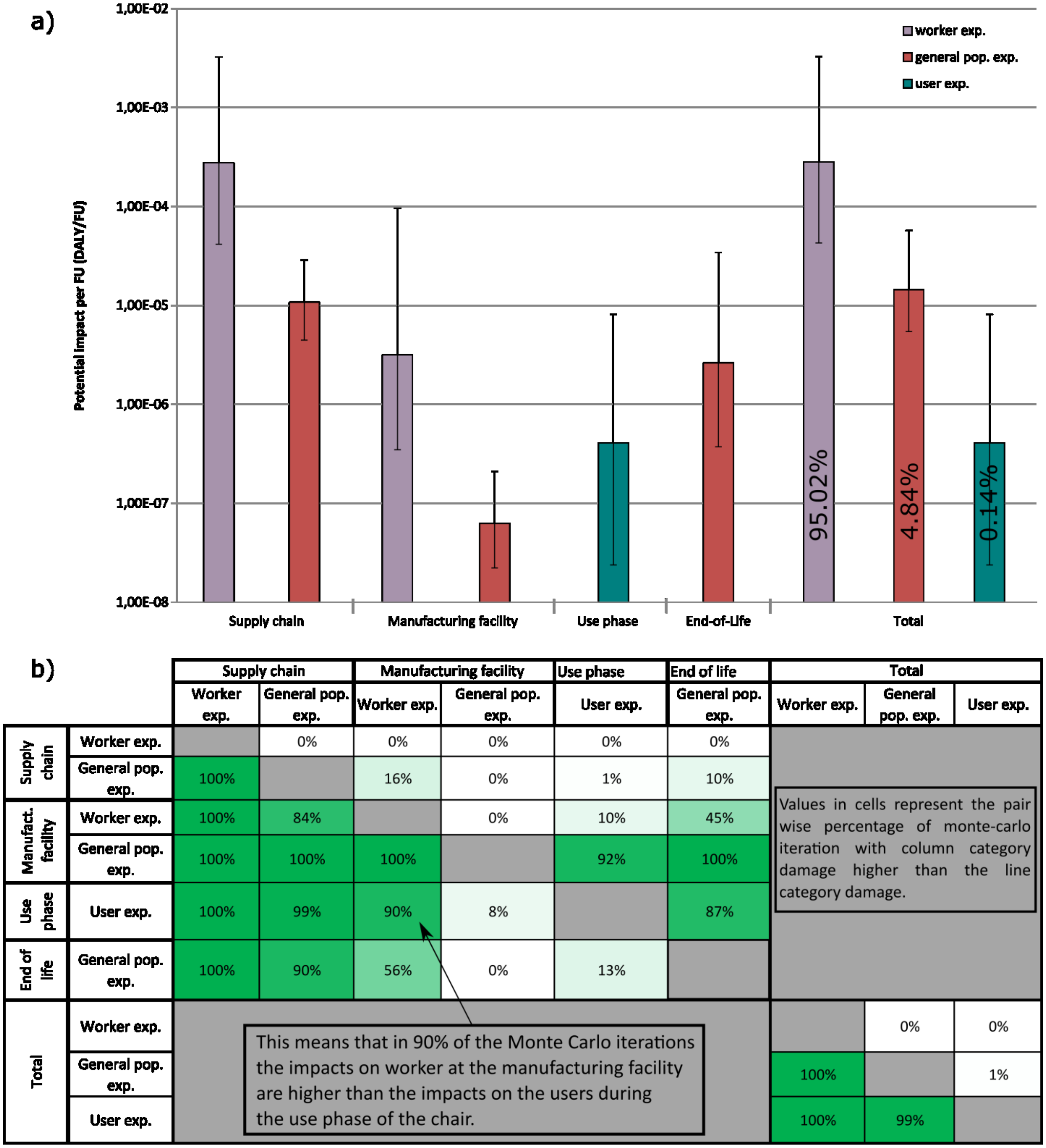
Figure 6.2 : Overall occupational human health impact per million $ final demand as a function of the total final demand for each commodity for the 279 commodities of the U.S. economy with the highest dollar-based impact intensity

We provide manufacturing facility and total (manufacturing facility and supply chain) characterization factors for occupational exposure to organic chemicals both in cancer and non-cancer cases and DALY with corresponding uncertainty data for 430 IO commodities (see supporting information Raw results worksheets in file SI.xlsx). Detailed data by chemical/commodity (235 organic chemicals and 430 commodities) are also provided (see file IO_chem_couple_data.csv: http://pubs.acs.org/doi/suppl/10.1021/acs.est.6b04434).

If we put the range of the impacts occurring in the manufacturing sectors of commodities in perspective: the impacts attributable to workplace fatal and nonfatal injuries and illnesses (from Scanlon et al. (2014), converted to impact per production \$) range from $3.2x10^{-7}$ to 0.33 WE-DALY per million \$ while the impacts of occupational exposure to organic chemicals range from $7.9x10^{-5}$ to 3.6 DALY per million \$.

6.2.3.2 Case study

The case study illustrates how potential impacts of occupational exposures may be linked to the functional unit of a product life cycle and provides a discussion on the relative importance between the supply chain and manufacturer facility and a comparison to other sources of potential human health impact, namely from indoor emissions in the use phase and from outdoor emission in all life cycle stages. Figure 6.3a) presents the potential human health impacts on a log scale for the use of an office lounge seat for five (5) years, with a total impact of $2.76x10^{-4}$ DALY per FU disaggregated by life cycle stage. The impact generated by general population exposure corresponds to the exposures to outdoor emissions occurring in the different life cycle stages. The supply chain stage is responsible for 97% (95% confidence interval: [89.3%-99.7%]) of the entire human health impacts over the entire life cycle. Human health impacts from worker exposure (blue bar, left Fig.3a) to organic substances are twenty times higher than those from general population exposure (red bar, left). The manufacturing facility impact is substantially lower than the supply chain, with 98% (95% confidence interval [87.4%-99.9%]) linked to worker exposure and only 2% (95% confidence interval [9.3 $x10^{-4}$%-12.5%]) to the general population. End-of-life represents only 0.88% of the total human health impact (95% confidence interval [$9.0x10^{-2}$%-6.7%]). The relative contribution from user exposure during product use amounts to only about 0.14% of the total impact (95% confidence interval [$6.3x10^{-5}$%-0.16%]). Worker exposure is 95.02% of the total impact (95% confidence interval [78.8%-99.4%]) and general population exposure is 4.84% of the total impact (95% confidence interval [0.55%-20.4%]). Figure 6.3b) shows the matrix of pair-wise comparisons for each category. Each individual percentage indicates the fraction of Monte Carlo iterations in which the d corresponding to the column is higher than the bar corresponding to the row. Rows are not meant to add up to 100%. In this case study, although occupational exposure impacts at the manufacturing facility and in the supply chain have overlapping 95% confidence intervals, the pair comparison matrix shows that occupational exposure impacts in the supply chain are higher than at the manufacturing facility in 100% iteration, thus confirming that use phase exposure is substantially lower than all other impacts (probability of false negative lower or equal to 13%), except for the impact of the manufacturing facility outdoor emissions on the general population (92% chance that use phase is higher). Figure 6.3a) adapted to different endpoints (cancer cases and non-cancer cases) may be found in the supporting information (see figures C.4 and C.5 in annex C).



		Supply chain		Manufacturing facility		Use phase	End of life	Total		
		Worker exp.	General pop. exp.	Worker exp.	General pop. exp.	User exp.	General pop. exp.	Worker exp.	General pop. exp.	User exp.
Supply chain	Worker exp.		0%	0%	0%	0%	0%			
	General pop. exp.	100%		16%	0%	1%	10%			
Manufact. facility	Worker exp.	100%	84%		0%	10%	45%			
	General pop. exp.	100%	100%	100%		92%	100%			
Use phase	User exp.	100%	99%	90%	8%		87%			
End of life	General pop. exp.	100%	90%	56%	0%	13%				
Total	Worker exp.								0%	0%
	General pop. exp.							100%		1%
	User exp.							100%	99%	

Values in cells represent the pair wise percentage of monte-carlo iteration with column category damage higher than the line category damage.

This means that in 90% of the Monte Carlo iterations the impacts on worker at the manufacturing facility are higher than the impacts on the users during the use phase of the chair.

Figure 6.3: a) Human health impacts associated with the use of an office lounge seat for 5 years, detailed by life cycle phase and impact cause with 95% confidence interval; b) Matrix of pair-wise Monte Carlo superiority for each bar of a)

Figure 6.4 compares the manufacturing facility impact due to occupational exposure to organic chemicals to the manufacturing facility, supply chain and total impacts due to occupational exposure to organic chemicals for each of the first-tier suppliers. There is a difference of over three orders of magnitude between the most impacting supplier and the least impacting one.

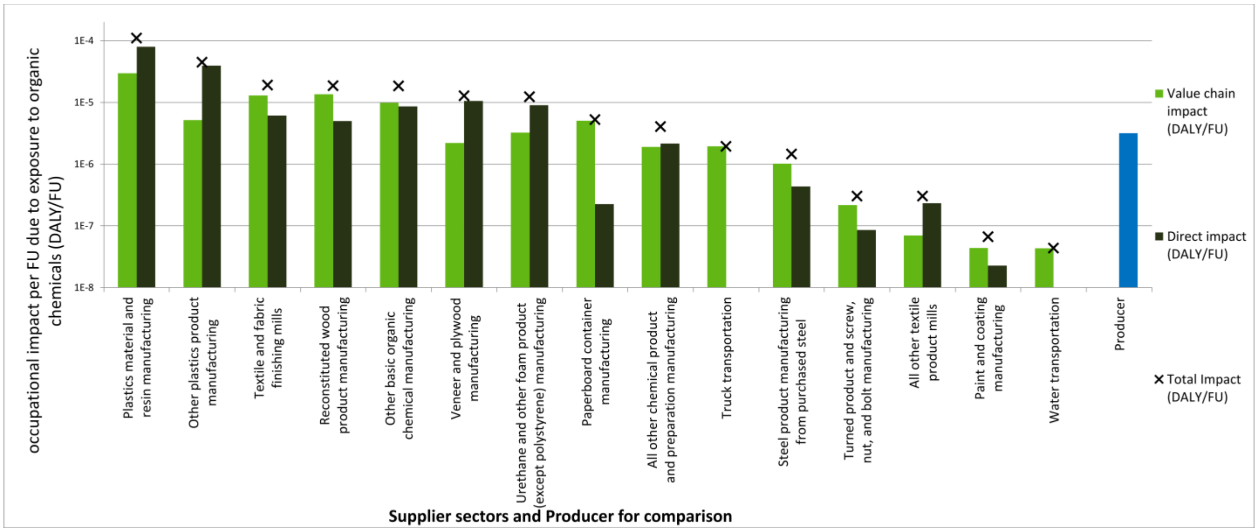


Figure 6.4: Manufacturing facility and supply chain human health impacts associated with the use of an office lounge seat for 5 years due to occupational exposure to organic chemicals for each first-tier supplier commodities compared to impacts at the chair manufacturing facility level (blue)

The computer scripts developed for this research are available in the supporting information (https://github.com/gaelkijko/occ_expo_lca). We also provide a computer script to generate a figure representing the structure of the supply chain as seen in the TOC/art figure (see figure C.6). It incrementally disaggregates the data using a width-first approach derived from Bourgault, Lesage et Samson (2012), showing how the first-tier suppliers play a dominant role, especially when compared to the manufacturer.

6.2.4 Discussion

This research broadens the scope of the occupational exposure framework in Kijko, Gaël et al. (2015), which solely focuses on the production site, to include the full supply chain. The approach provides occupational impacts per dollar produced for each economic commodity, differentiating the manufacturing facility impacts from supply chain impacts. It enables LCA practitioners to use available company-specific primary data on hours worked per FU and on measured local concentrations at the workplace and add sector-specific IO data to fill in gaps at the producer level and extend the assessment to the entire supply chain. For instance, the total hour inventory matrix (see file SI.xlsx in supporting information) provides factors to calculate commodity-specific BCWH when company-specific data are not available. Table C.3 and section SI-3 in the Annex C further detail how to combine this article's dollar based impact intensities, hour based impact intensities per BCWH worked (Kijko, Gaël et al., 2015) and available data when calculating the impact on workers for a product system including the supply chain. When assessing the entire U.S. industry, the research shows that impacts in sectors with high supply chain dollar-based impact intensity are mainly generated by occupational impacts due to exposure at the manufacturing facility level. The lower the impacts over the life cycle, the higher the relative contribution of occupational exposure in the supply chain, thus affirming the significance of including the entire supply chain when assessing occupational impacts. This research may be of direct use in environmental and social LCAs since human health impacts are relevant to both approaches. The estimation of labor hours of blue collars workers over the entire supply chain using input-output data carried out in the present paper is consistent with the labor footprint and labor impact category assessed in social LCA (Alsamawi et al., 2014).

The case study demonstrates a consistent approach to integrate the consideration of worker health impacts attributable to chemical exposures across the product life cycle. The findings from the case study indicate that worker health impacts may be significant when compared to the general population. These findings support the inclusion of worker health impacts in the LCA framework. The results presented here are coherent with those detailed by Pettersen et Hertwich (2008) since both articles demonstrate that occupational impacts, whether from accidents and injuries or from exposure to chemicals at work, can be the main contributors to human health impacts. It is important to note that the results obtained here in the specific case study highly rely on the type of product studied: the results would differ for other products such as cosmetics, for which direct application may play a more important role (Jolliet et al., 2015).

In the specific case study outlined here, if the seat producing company is willing to reduce the human health impact of its product life cycle, it should focus on occupational impacts related to chemical exposure in the workplace. Rather than investing every effort in their own production steps, the company should also address the seat supply chain and the commodities that dominate the supply chain impacts for which an effort should be made to obtain more information (see Figure 6.4).

Several limitations apply to the approach and its field of application must be clearly defined. First, it is devised as a comparative analysis and the absolute impacts must be considered very carefully. Health impacts relying on sector or commodity averages are not necessarily representative of specific conditions at a given manufacturing site. Actual measurements at the production facility should be used whenever possible. Second, since the IO model consists of 430 commodities, these commodities are an aggregation of multiple individual commodities produced by multiple individual industries and therefore reduce the representativeness of the economic links. For example, the *336300 - motor vehicle suppliers commodity*, which includes everything from engine parts to windshields, requires very different chemicals in the production. A model with finer granularity would decrease the uncertainty linked to representativeness and increase the need for data. We believe that the method provides a good trade-off between data availability and granularity. Third, the results detailed here were developed and validated for the US context and should not be used for countries with different manufacturing and worker safety practices. However, corresponding CFs and inventory factors could potentially be generated for any given country for which the following data are available: workplace concentrations of chemicals, BCWH worked and an IO economic model. The level of detail of the available data will directly impact the granularity of CFs and inventory factors. Fourth, the use of a national economic model limits the scope of the analysis since purchases of international product are aggregated as imports without detail on the origin of the purchase (commodity or country). Thus, the impacts of imports can only be calculated as equivalent to national production. To be able to account for international industrial dependencies, a multiregional IO model (such as the Eora MRIO Database (Lenzen, Moran, Kanemoto, & Geschke, 2013) and the Exiobase (Tukker et al., 2013)) along with concentrations and BCWH worked for each country are required.

Measured concentrations used to calculate occupational exposure account for both occupational and outdoor far-field emissions. The risk of double counting when factoring in worker exposure to far-field outdoor emissions is negligible due to the much lower intake fraction associated with outdoor emissions.

The dissemination of the results and uncertainty is also very important in LCA, and this article provides an innovative way to communicate them, especially through the development of a matrix of pair-wise Monte Carlo superiority (see Figure 6.3) and the visualization of contributions across supply chain levels (see Figure C.6 in Annex C).

While this article focuses on occupational exposure to organic chemicals, it does not account for metals and other inorganics that may also represent substantial exposures and impacts. The approach may and should be extended to all airborne exposures for which both occupational concentrations and effect factors are available. In this respect, the contribution of occupational exposure to the overall life cycle human health impacts of the office lounge seat may increase if impacts from particulate matter and inorganic chemical exposure are accounted for. Any research providing sectoral impact data per hour worked in occupational settings (from accidents, exposure to noise and vibrations, for example) may benefit from being coupled with the proposed approach.

CHAPITRE 7: RÉSULTATS COMPLÉMENTAIRES ET DISCUSSION

Des résultats complémentaires ont été obtenus durant ce projet de recherche mais n'ont pas fait l'objet d'une publication scientifique. Le présent Chapitre présente ces résultats.

7.1 Extension à d'autres polluants

La méthode développée et testée aux chapitres précédents est limitée uniquement aux polluants organiques existant dans USEtox et se base sur des concentrations professionnelles mesurées entre 2002 et 2009.

7.1.1 Mise à jour des CF et extension à l'ensemble des polluants caractérisés dans USEtox

Le développement méthodologique effectué dans ce projet de recherche a été réalisé en parallèle du développement d'un script informatique (langage python) permettant de générer des CF de manière automatique à partir des données sources nécessaires (concentrations mesurées, structure des classifications industrielle et économique, modèle IO, statistiques de production et d'heures travaillées…).

USEtox fournit des facteurs d'effets pour 3080 substances organiques (dont 932 substances avec au moins un facteur d'effet strictement positif pour une exposition par inhalation) et 30 substances inorganiques (dont 21 avec au moins un facteur d'effet strictement positif pour une exposition par inhalation). La base de concentration, développée au Chapitre 5 et donc les FC calculés aux Chapitres 5 et 6 n'incluent que 235 substances.

Un autre polluant en milieu de travail est la matière particulaire. Il est démontré qu'en dessous d'un certain diamètre aérodynamique, la poussière pénètre profondément dans les poumons et favorise le développement de cancers (Heyder, 2004; Pope et al., 2002). Les poussières que nous considérons sont celles avec un diamètre aérodynamique de moins de 2.5 micromètre (PM2.5). Gronlund et al. (2015) ont calculé un facteur d'effet de 78 DALY par kg de PM 2.5 inhalé. Cela correspond à une dose d'effet touchant 50% de la population (ED50) de 7.37×10^{-2} cas de cancer par kg de PM2.5 inhalé.

La base de concentration de polluants en milieu de travail aux États-Unis (É-U) comprend des mesures de particules dans l'air, mais elle correspond à une mesure des PM10 (particules dont le diamètre aérodynamique est inférieur à 10 µm. Le calcul de la fraction de PM2.5 dans des PM10 est dépendant de l'activité effectuée. Un document de l'état de l'Orégon (É-U) présente des fractions très variables : entre 6% pour le concassage de roche et 100% pour une chaudière au gaz naturel (Oregon Department of Environmental Quality, 2011). De plus, les concentrations en milieu de travail sont représentatives de toutes les sources présentes. Afin de pouvoir estimer un impact de ces concentrations de PM10 l'hypothèse selon laquelle 75% des PM10 sont des PM2.5 a été utilisée. Une analyse de sensibilité considérant que seulement 10% des particules est aussi réalisée. Finalement, les années prises en compte pour les concentrations en milieu de travail sont comprises entre 2005 à 2015.

Lors de la mise à jour des FC, 233 substances ont été caractérisées. Cela signifie que 233 substances ont à la fois des concentrations dans la base de l'OSHA et un facteur d'effet dans USEtox. Il est intéressant de noter que lors de la mise à jour des CF, bien que les substances inorganiques et les PM aient été inclues en plus des substances organiques, le nombre de substances uniques faisant l'objet du calcul de FC a diminué. Le nombre d'enregistrement dans la base de l'OSHA a diminué de manière importante entre les années 1988 et 1994 et reste depuis à un niveau stable. La Figure 7.1 présente l'évolution du nombre de mesures dans la base de l'OSHA entre 1984 et 2015. Les mesures personnelles et non personnelles sont distinguées car la méthode présentée dans ce projet de recherche se base sur des mesures personnelles (qui représentent l'exposition réelle des travailleurs). De plus, nous différencions les mesures personnelles témoins des mesures personnelles non témoins car les mesures témoins sont utilisées pour confirmer que l'appareillage de mesure ne détecte pas de polluants lorsqu'il n'est pas exposé. Bien que ces mesures soient importantes, elles ne sont pas pertinentes pour calculer l'exposition des travailleurs.

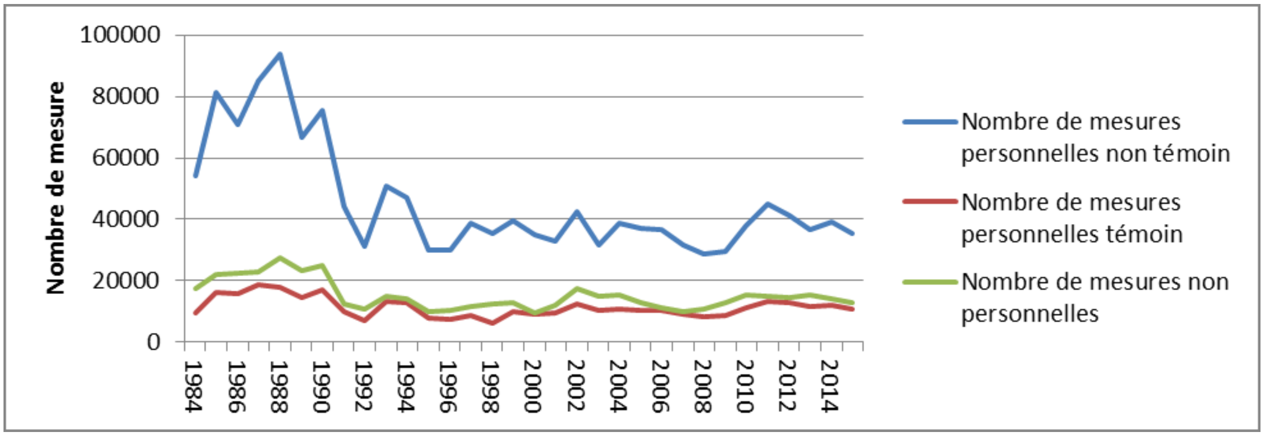


Figure 7.1 : Évolution du nombre de mesures dans la base de l'OSHA entre 1984 et 2015

La Figure 7.2 présente le nombre de substances différentes pour lesquelles des mesures existent dans la base de données de l'OSHA depuis sa création. Le nombre moyen de mesures personnelles non témoin est aussi indiqué, et bien que le nombre total de mesures dans la base est restée stable dans les 20 dernières années, il est important de remarquer que le nombre de substances diminue et le nombre de mesures personnelles non témoin par substance à tendance à augmenter.

Cela explique la diminution du nombre de substances couvertes par des FC lors de la mise à jour des résultats.

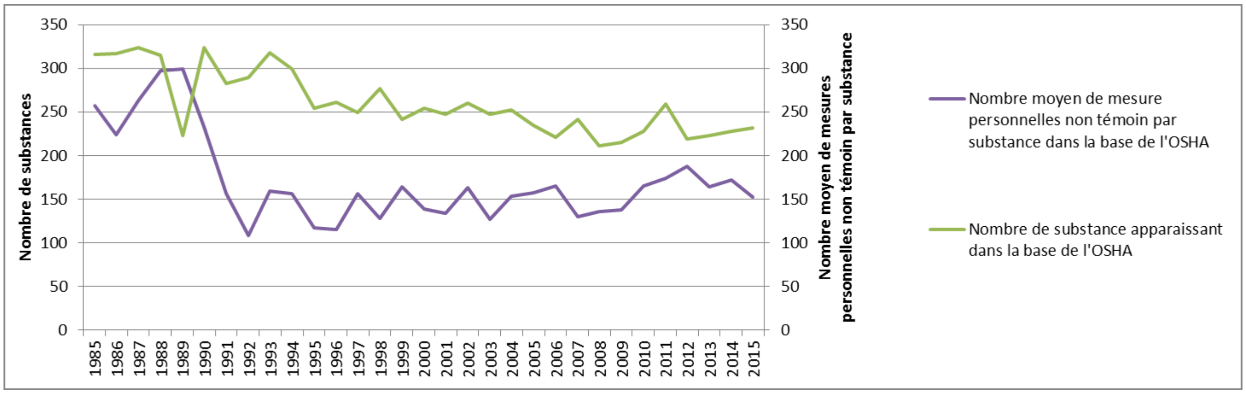


Figure 7.2 : Évolution du nombre de sustances et du nombre de mesures personnelles non témoin dans la base de l'OSHA entre 1984 et 2015

Les Figure 7.3 et Figure 7.4 présentent les facteurs de caractérisation et les scores d'impact par secteur industriel (surface de chaque histogramme) mis à jour. Sur la base de l'hypothèse que 75% des matières particulaires ont un diamètre inférieur à 2.5 µm, les PM dominent largement les impacts comparativement aux autres substances (Figure 7.3). D'un point de vue global, l'impact annuel de la production manufacturière aux États-Unis atteint $4{,}1\text{x}10^6$ DALY dont $3{,}3\text{x}10^6$ DALY attribuables aux PM, soit 80% de l'impact global. Une analyse de sensibilité est alors proposée considérant que seulement 10% des particules ont un diamètre inférieur à 2.5 µm (Figure 7.4). La contribution relative de ces dernières à l'impact total diminue pour atteindre 35%. En comparant les sept substances les plus impactantes à celles identifiées au Chapitre 5, l'acide chromique (incluant les chromates) et le Benzo[a]Pyrene apparaissent maintenant en troisième et quatrième position. Les courbes cumulatives montrent que 75% des dommages sur la santé humaine ont lieu dans environ 18 des 81 secteurs correspondant 29% des heures totales travaillées.

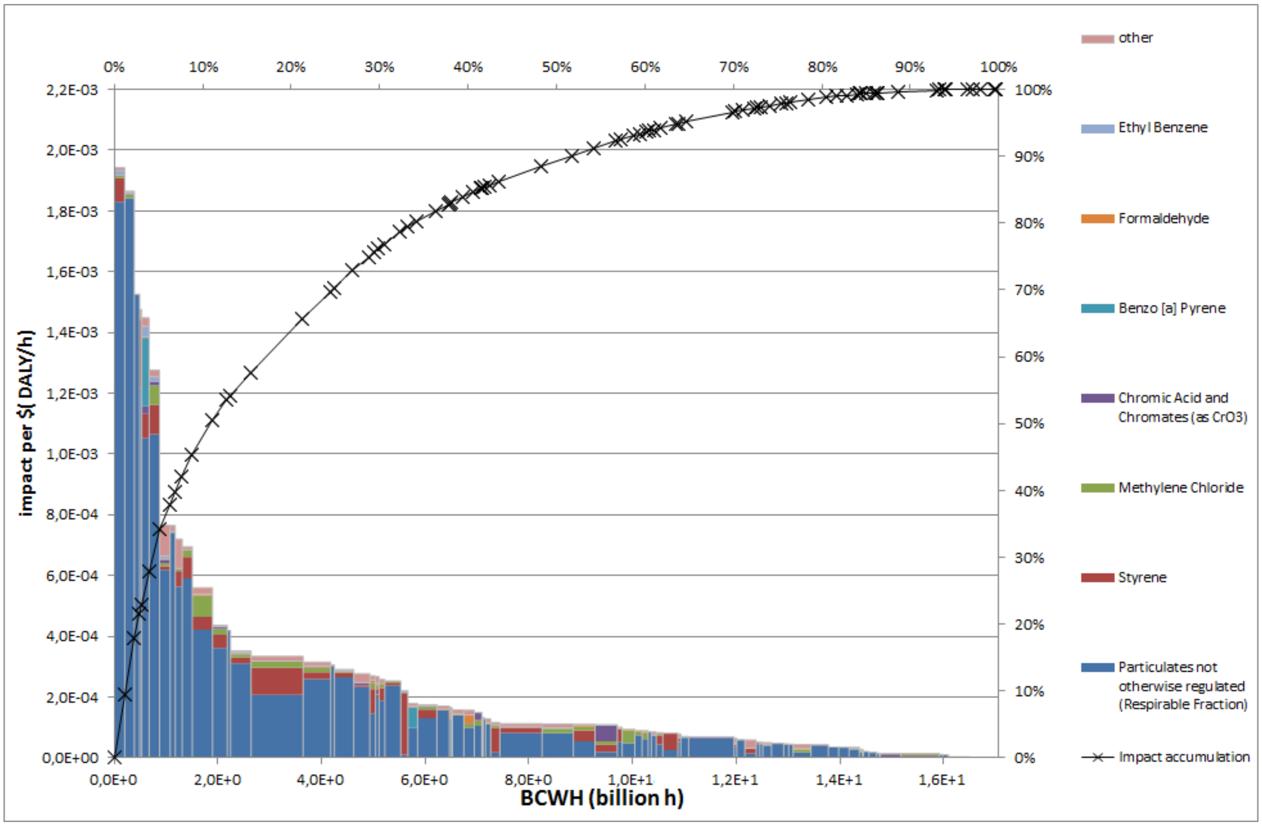


Figure 7.3 : Répartition des impacts directs par heure travaillée pour l’ensemble des substances dans OSHA et pour lesquelles des facteurs d’effet sont disponibles dans USEtox. Résultats groupés en 81 secteurs.

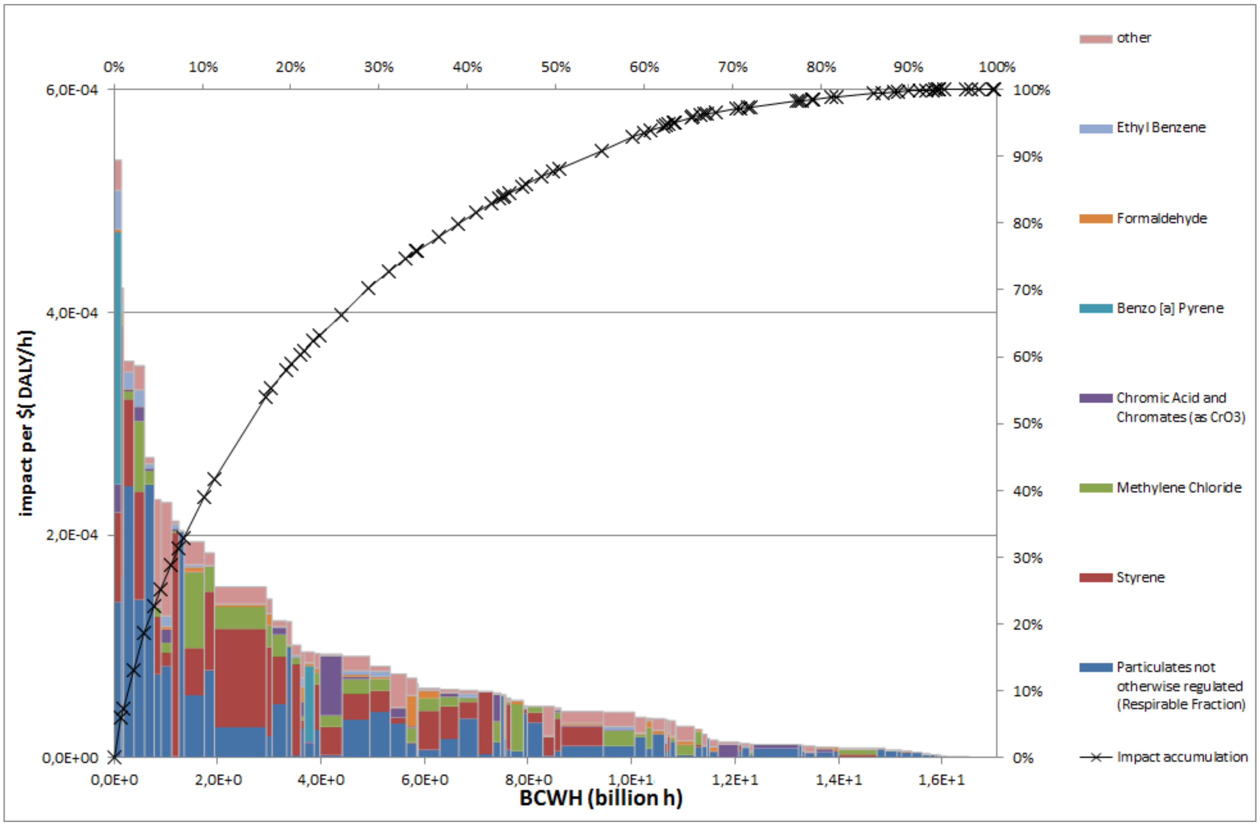


Figure 7.4 : Répartition des impacts directs par heure travaillée pour l'ensemble des substances présentes dans la base de l'OSHA et dans USEtox, avec la fraction de PM2.5 dans le PM10 fixée à 10%

Trois substances ne sont plus dans la liste des 7 substances le plus impactantes suite à la mise à jour des FC : le trichloréthylène, le tetrachloroéthylène et le méthacrylate de méthyle. Ces substances font toujours l'objet de mesures en milieu de travail.

Figure 7.5 et Figure 7.6 présentent la distribution des dommages entre chaque secteur de production de commodité et leur chaîne de valeur pour l'industrie américaine. Comme identifié au Chapitre 6 avec l'analyse des substances organiques, les commodités avec un impact par dollar de production élevé sont celles qui ont un impact par $ élevé dans leurs secteurs respectifs de production en avant plan. Les points extrêmes dans la Figure 7.5 sont dominés par les impacts potentiels des PM (le secteur le plus impactant quand les PM sont prises en compte est le « *Truck trailer manufacturing* » avec 97% des impacts provenant des PM).

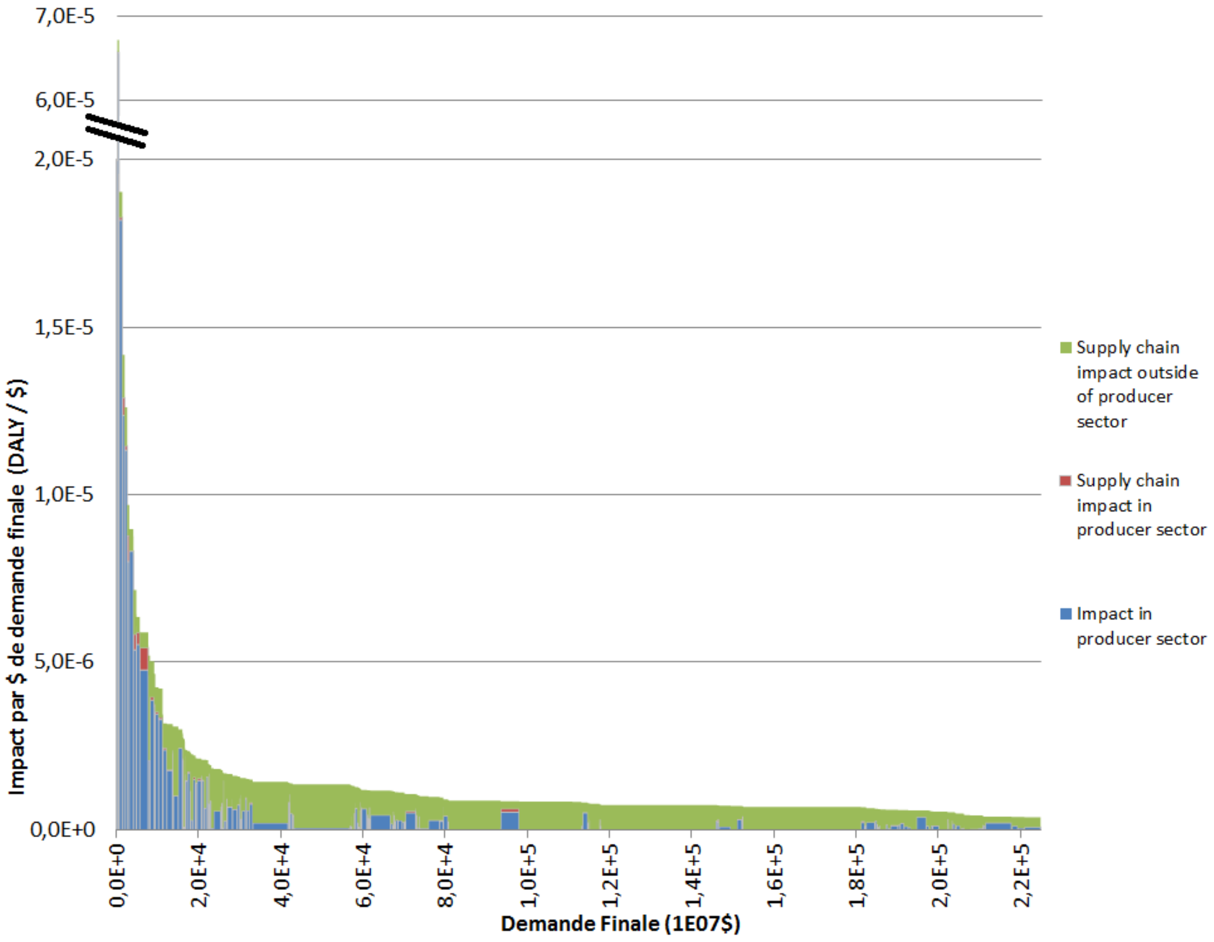


Figure 7.5 : Répartition des impacts totaux par $ de demande finale pour toutes les substances

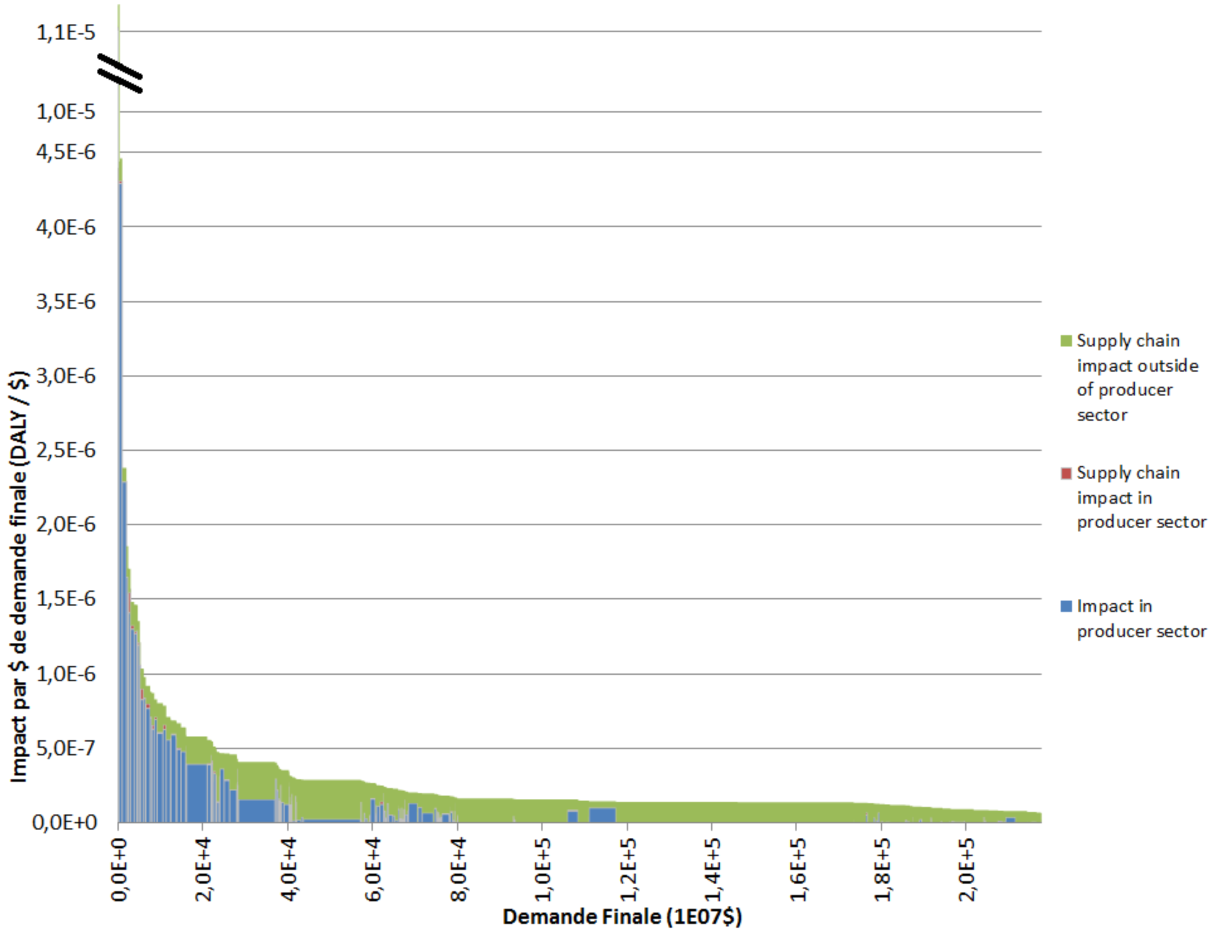


Figure 7.6 : Répartition des impacts totaux par dollar de demande finale sauf pour les PM

Cette mise à jour met a permis de générer des CF pour calculer les impacts sur les travailleurs des expositions professionnelles aux polluants. Ils sont directement utilisables dans le cadre d'étude ACV. La méthode développée aux Chapitres 5 et 6 est maintenant opérationnelle.

7.1.2 Extension à d'avantage de substances

USEtox ne couvre pas l'intégralité des substances pour lesquelles des concentrations en milieu de travail sont disponibles dans la base de l'OSHA : pour la période 2005-2015, des concentrations sont disponibles pour 373 substances dont seulement 233 ont un facteur d'effet dans USEtox.

Les facteurs d'effet d'USEtox sont développés à partir de données toxicologiques généralement publiées dans des articles scientifiques, mais ces études sont coûteuses et longues. Une opportunité pour étendre la couverture des substances au-delà de celles présentes dans la base de donnée actuelle de USEtox s'est présentée lorsque l'Union Européenne, via l'agence européenne des produits chimiques (ECHA), a mis en place une base de donnée publiquement consultable contenant les dossiers d'autorisations pour toutes les substances chimiques produites ou distribuées en Europe assujetties à la réglementation REACH, et que les industriels doivent enrichir.

Avec des collègues de l'Université Technologique du Danemark (DTU), nous avons testé la faisabilité d'utiliser les données de REACH pour générer davantage de facteur d'effet et augmenter le nombre de substances à caractériser. Pour ce faire un script d'extraction de données de l'ECHA a été développé en utilisant le langage python. La base de REACH ne permet pas un accès direct aux données, mais permet de consulter un nombre variable de page pour chaque dossier (de 10 à plus de 400). Le script développé permet l'extraction sélective du contenu des pages. Une fois les pages extraites, les données sont isolées à l'aide d'autres scripts en langage python.

L'analyse des données extraites de REACH a été pilotée par l'équipe de recherche de DTU et a fait l'objet d'une publication pour laquelle je suis co-auteur (Müller, de Zwart, Hauschild, Kijko, & Fantke, 2016).

Dans cet article, des données toxicologiques ont été identifiées pour plus de 15000 substances. Mais un grand nombre de ces données sont pour des expositions aigues. En ACV, les données toxicologiques chroniques sont privilégiées lors du calcul de CF avec la méthode USEtox. De plus REACH requiers une analyse basée sur l'espèce la plus sensible. Bien que ce type d'étude soit adapté dans un contexte d'analyse des risques, il ne l'est pas pour l'ACV car un CF basé sur l'espèce la plus sensible va induire une surestimation des dommages potentiels. La conclusion de cet article est que le potentiel de la base de données REACH est grand mais un effort important est désormais requis pour vérifier les données sachant que seuls 5% des dossiers font l'objet de vérification de conformité. La validation des données REACH nécessaire au calcul de nouveaux EF est possible mais dépasse l'objet de ce projet de recherche.

7.1.3 Limitation

Malgré l'utilisation de données récentes, les CF calculés souffrent de deux principales limitations :

1. Ordre de grandeur
2. Certaines substances (en particulier les PM et les substances inorganiques) s'appuient sur des hypothèses et des données toxicologiques très incertaines
3. Les données utilisées ne proviennent que des États-Unis et ne prennent pas en compte les importations

7.1.3.1 Ordre de grandeur

Les résultats étendus aux substances inorganiques et PM semblent montrer que les impacts sur les travailleurs sont encore plus important que les CF obtenus au Chapitre 5. Mais il est important de garder un œil critique sur ces CF : à eux seuls, les PM2.5 atteignent 1,8x10^{-3} DALY/h dans le secteur le plus impactant. Sachant qu'une année de travail représente environ 2000 heures, cela revient à dire que pour une année de travail, un travailleur de ce secteur perdrait 3,6 années de vie en bonne santé. Bien que l'ACV ait une vocation comparative et non absolue, de tels résultats rendent nécessaire de mieux étudier le facteur d'effet spécifique aux PM2.5.

7.1.3.2 PM et substances inorganiques

Les concentrations de PM fournies dans la base de données de l'OSHA correspondent à des particules avec un diamètre aérodynamique inférieur ou égal à 10 µm (PM10). Le facteur d'effet calculé par Gronlund et al. (2015) est spécifique aux particules avec un diamètre aérodynamique inférieur ou égal à 2.5 µm (PM2.5). Afin d'estimer la part des PM2.5 dans les PM10, une recherche bibliographique a permis d'identifier un document publié par l'état de l'Orégon (Oregon Department of Environmental Quality, 2011) qui identifie la fraction de PM2.5 dans les PM10 émises par différents équipements. Toutefois, ces données ne peuvent être facilement utilisées pour représenter le milieu de travail : les mesures fournies par l'OSHA prennent en compte les contributions de toutes les sources présentes en milieu de travail. En l'absence d’information sur les équipements présents, toute approximation sur la fraction de PM2.5 dans les PM10 mesurées sera très incertaine.

Dans un deuxième temps, le facteur d’effet utilisé pour calculer un impact potentiel à partir d’une quantité de PM inhalé introduit aussi une incertitude importante. Le facteur fournit par Gronlund et al. (2015) a été développé pour de faibles concentrations. Apte, Marshall, Cohen et Brauer (2015) ont aussi montré que les courbes de relation entre la concentration de PM2.5 et la mortalité ne sont pas linéaires. Pour des concentrations importantes comme mesurées dans certains secteurs industriels, le fait d’utiliser une relation linéaire dose-réponse risque d’entraîner une surestimation importante des impacts.

7.1.3.3 Imports et cadre géographique

La méthode présentée au Chapitre 6 s’appuie sur un modèle Input-Output pour calculer les CF incluant la chaîne de valeur. Le modèle utilisé, CEDA (Suh, S., 2004), est spécifique aux États-Unis et exclu les imports de la demande finale. La demande finale représente les biens consommés par les utilisateurs finaux : population, gouvernements et collectivités, exports, changements de stocks. Toute consommation d’un bien par une industrie est considérée comme une demande intermédiaire et n’est pas prise en compte dans la demande finale. La conséquence directe de l’utilisation d’un tel modèle pour calculer les CF est que l’impact modélisé est spécifique à l’industrie des États-Unis et aucune distinction n’est possible entre un bien importé ou un bien produit aux US. L’incertitude de cette hypothèse sous-jacente au choix de modèle IO n’est pas quantifiée dans cette thèse. Toutefois au vu des différences importantes entre les moyens de production et standards de protection des travailleurs à l’échelle mondiale, il apparait important d’évaluer la pertinence d’utiliser les CF fournis dans cette thèse en dehors du contexte des États-Unis. Mais même dans un contexte États-Unien cette hypothèse peut être problématique : les États-Unis extraient beaucoup moins de fer que ce qu’ils consomment (Suh, S., 2004). Donc si on étudie les impacts de de la production de fer, les impacts calculés aux moyen des CF fournis seront sensiblement faussés et seront représentatifs de la technologie d’extraction utilisée aux États-Unis alors que la plupart du fer disponible sur le marché aux États-Unis est importé.

7.2 Retour sur l'interprétation des résultats d'incertitude

Au cours de la réalisation du cas d'étude, au Chapitre 6, un outil d'interprétation de résultats probabilistes en ACV a été développé : la représentation matricielle présentée à la Figure 6.3 permet de comparer des scénarios ou des étapes d'un cycle de vie entre elles tout en prenant en compte les corrélations entre les incertitudes dans les calculs.

7.2.1 Une représentation inadaptée

L'idée de cet outil vise à interpréter des résultats ACV lorsque présentés sur un graphique tel que la Figure 7.7**Error! Reference source not found.**. Les histogrammes sont présentés côte à côte afin de faciliter la comparaison entre scenarios alors que les barres d'incertitudes présentent l'incertitude sur la « hauteur » de chaque colonne (traditionnellement sous la forme d'intervalles de confiance à 95%). Dans le cas de la comparaison des colonnes A et C une interprétation courante est de dire qu'aucune conclusion n'est possible car les intervalles de confiance se chevauchent.

En ACV, la méthode principale de propagation de l'incertitude est l'analyse de Monte Carlo. Cette méthode consiste à faire n itérations du calcul en tirant au hasard, pour chaque donnée d'entré une valeur selon une loi de distribution spécifique et à calculer le résultat d'impacts potentiels (dans le cas de la Figure 7.7 la hauteur de chaque colonne serait calculée à chaque itération). A titre d'exemple, au lieu d'utiliser un facteur d'effet (EF) constant pour calculer les impacts potentiels sur la santé humaine dans toutes les itérations, un tirage aléatoire dans la distribution représentant la valeur probable d'EF sera effectué à chaque itération.

Imaginons deux cas extrêmes en utilisant la Figure 7.7 :

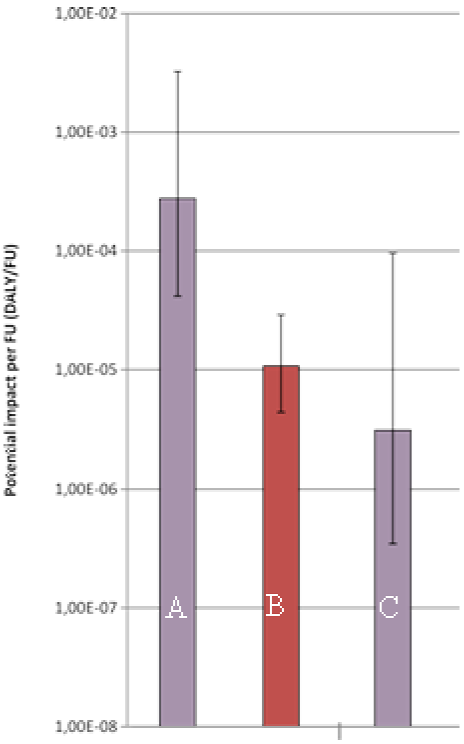


Figure 7.7 : Exemple de résultat d’AICV

Cas 1 : Corrélation totale

Les barres A et C représentent le score d’impact du à l’exposition d’une seule et même substance et sont en conséquence entièrement corrélées (Dommage = Quantité prise x EF x Sévérité). Sous l’hypothèse que les quantités prises ainsi que la sévérité sont connues et n’ont pas d’incertitude associée, on peut en conclure que la quantité prise de la colonne A est supérieure à celle de la colonne C.

Lors de chaque itération, la quantité prise de la colonne A est supérieure à celle de la colonne C et donc quelle que soit l’itération la hauteur de la colonne A sera supérieure à la colonne C. Dans ce cas, malgré le chevauchement des barres d’incertitude une conclusion pourrait être atteinte : A est plus impactant que C.

Cas 2 : Indépendance totale

Supposons maintenant que les barres A et C correspondent à l’impact de deux substances différentes (A et C) ayant des modes d’actions totalement différents. Si on considère toujours que : Dommage = Concentration x EF x Sévérité et sous l'hypothèse que la quantité prise de A est la même que celle de C, on peut en conclure que l'EF de A est supérieur à l'EF de C.

Dans le cas d'indépendance totale, à chaque itération du calcul probabiliste les facteurs d'effet de la substance A et C sont tirés au hasard et de manière indépendante selon leur distribution d'origine. Bien que la valeur déterministe de l'EF de A soit supérieure à celle de l'EF de C, il n'est pas garanti qu'à chaque itération du Monte Carlo la valeur tirée de la distribution de A soit supérieure à celle tirée de la distribution de C. La Figure 7.8**Error! Reference source not found.** présente un tel cas : les deux distributions de valeur des deux EF se chevauchent alors que les valeurs déterministes sont différentes.

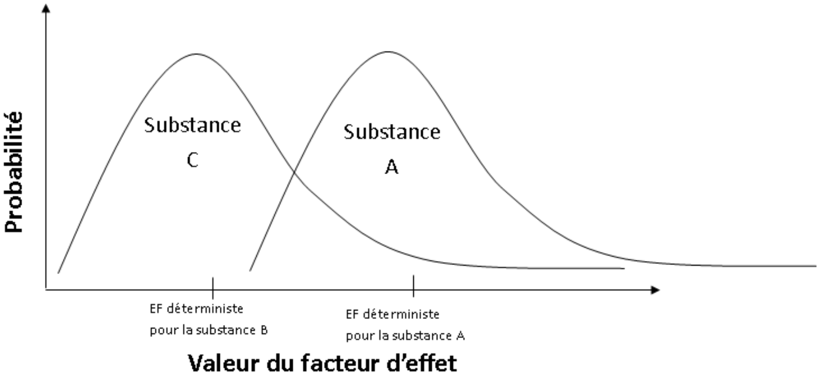


Figure 7.8 : exemple de distributions autour de valeur déterministes

Dans cette situation il ne sera pas possible de conclure avec certitude lequel des deux scenarios est le meilleur comme pour le cas 1, mais il sera possible de déterminer le pourcentage des itérations du Monte Carlo pour lesquels les résultats de A sont plus grands que les résultats de C.

7.2.2 Un outil comparatif intégrant l'incertitude

Comme présenté au point précédent et dans la Figure 7.7, la simple présence de barres d'incertitude n'est pas pertinente pour conclure sur la (non) significativité de la différence entre les résultats des scenarios comparés. Elles peuvent même induire en erreur une personne voulant interpréter un tel graphique.

Nous proposons une approche ou les données pertinentes de chaque itération du Monte Carlo (i.e. inputs et résultats du modèle) sont conservées dans une matrice qui permet de comparer directement les résultats issus de chaque tirage. Sur un total de n itérations on pourra dériver la fréquence à laquelle le résultat d’un scenario est supérieur à l’autre comme dans la Table 7.1. Chaque case de cette matrice présente la fraction des itérations du Monté Carlo (ou fréquence) pour lesquelles les résultats des scenarios de chaque colonne (X) du tableau sont plus grands que les résultats des scenarios de chaque ligne (Y).

Tableau 7-1 : Matrice de comparaison directe entre scenarios (A, B et C)

X>Y		X		
		A	B	C
Y	A		0%	0%
	B	100%		16%
	C	100%	84%	

Deux limitations importantes ont à prendre en compte :

Pour construire cette matrice, il faut que le logiciel (ou script informatique) effectuant la simulation de Monte Carlo conserve toutes les données nécessaires, ce qui peut représenter une quantité importante de données (proportionnelle au carré du nombre de catégories à comparer).

Afin d’avoir une comparaison pertinente, les incertitudes doivent être prises en compte depuis leur sources : si des données agrégées sont utilisées, alors on perd définitivement l’information sur la corrélation possible entre les sources d’incertitudes initiales. En prenant l’exemple du cas d’étude présenté au présent chapitre, pour pouvoir construire la matrice de comparaison directe, il a fallu, à chaque itération de la simulation de Monte Carlo, recalculer les concentrations de polluants dans chaque secteur pour obtenir les CF de chaque secteurs industriels, ce qui a pris environ 8h de calcul (sur un ordinateur portable avec 4 cœurs).

Pour une AICV complète avec une méthode différente par catégorie d’impact, cela reviendrait à recalculer chaque FC à chaque itération du Monte Carlo.

7.3 Combinaison avec d’autres méthodes (actuel ch. 6.4)

Comme présenté dans l’article 1 (voir Chapitre 2), la méthode développée dans les Chapitres 5 et 6 peut être combinée avec des méthodes développées par d’autres auteurs dans le but d’obtenir une vision plus globale des impacts potentiels sur la santé des travailleurs sur l’ensemble du cycle de vie.

La méthode développée dans ce travail de recherche se focalise sur les expositions aux polluants par inhalation. Tout impact provenant d’exposition à d’autres dangers ne sont pas pris en compte. L’utilisation conjointe d’une méthode *damage-based* (voir Chapitre 2) est possible. À titre d’exemple notre méthode présentée aux Chapitres 5 et 6 pourrait être combinée avec la méthode développée par Scanlon et al. (2014), qui fournit une vision plus globale sur les dommages sur les travailleurs. Les CF spécifiques aux accidents du travail pourraient être utilisés, ainsi que ceux qui ne couvrent pas les maladies professionnelles dues à l’exposition aux polluants en milieu de travail. Les auteurs fournissent des FC spécifiques à 127 secteurs de l’industrie qui sont compatibles avec des données d’inventaire en ACV et des FC pour les accidents professionnels (blessures et décès) et les maladies professionnelles. Scanlon et al. se limitent à évaluer le secteur lui-même sans prendre en compte la chaîne de valeur mais le lien avec les données d’inventaire permet de rendre en compte l’ensemble du cycle de vie.

Les données utilisées par Scanlon et al. comprennent les causes des accidents ou maladie. Il est donc possible de générer des FC spécifiques à un danger. Il existe toutefois un risque de double comptage combinant notre méthode avec celle de Scanlon et al. si on ne se soucie pas d’exclure les maladies professionnelles causées par des expositions à des substances chimiques par inhalation déjà considérées dans notre méthode. Les FC pour les accidents de travail de Scanlon et al. par contre sont parfaitement complémentaires avec notre méthode et ne pose pas de dangers de double comptage, car ils ne capturent que des impacts liés à des évènements soudains et donc excluent les maladies professionnelles.

7.5 Mise en perspective avec la réglementation en milieu de travail

Lors de la définition du projet de recherche, plusieurs avenues ont été explorées afin de choisir une base pour calculer les FC. Une de ces avenues concerne les limites d'expositions professionnelles fixées dans la réglementation. Comme la méthode développée n'est aucunement liée aux aspects réglementaires, le travail effectué n'a pas fait l'objet de publication mais est important dans le contexte du choix de proxys pour des pays ne publiant pas de concentrations de polluants en milieu de travail.

7.5.1 Réglementation des polluants en milieu de travail et ACV

Contrairement aux expositions de la population due aux émissions extérieures de polluants qui sont indirectement réglementées par des lois encadrant les émissions des industries, les expositions des travailleurs font généralement l'objet de réglementation limitant les concentrations de substances chimiques en milieu de travail. Mais le fait qu'une réglementation existe pour les expositions aux produits chimiques en milieu de travail ne signifie pas une absence d'impact, ni un réel contrôle des expositions. En supposant que toutes les entreprises situées aux États-Unis respectent les niveaux limites d'exposition des travailleurs, ces expositions entrainent tout de même un impact. L'existence de niveaux limites d'exposition correspond à une notion de niveau de risque acceptable et donc de niveau de dommage acceptable (Ale, 2005).

Certaines méthodes proposées en ACV reposent sur l'utilisation de limites d'exposition professionnelles (LEP) (Schmidt, AndersC, Jensen, Clausen, Kamstrup, & Postlethwaite, 2004a, 2004b; Schmidt, A. et al., 2004). Non seulement ces approches ne sont pas compatibles avec les principes qui soutiennent la caractérisation de l'exposition aux polluants pour déterminer les impacts potentiels sur la santé humaine en ACV, mais de plus les réglementations ne sont pas identiques dans tous les pays ce qui rend difficile l'agrégation géographique des impacts. De plus, même si deux pays ont des réglementations similaires, l'application réelle des niveaux limites prescrits peut varier de manière importante rendant difficile l'utilisation directe de l'information réglementaire pour développer des proxys pour d'autres pays.

Durant le développement de la méthode, lors de l'analyse des résultats présentés au Chapitre 5, la question de la cohérence des LEP s'est posée : est-ce qu'en se basant sur les études toxicologiques existantes, les LEP correspondent à un risque accepté similaire entre les substances couvertes?

Pour répondre à cette question, trois des substances identifiées parmi les plus impactantes ont été comparées : dichlorométhane, trichloréthylène et tetrachloroéthylène.

La Tableau 7-2 présente une analyse succincte des LEP pour chacune de ces substances: celle de l'OSHA et celle de l'association américaine pour la promotion de la santé au travail et de l'environnement (ACGIH). La première est réglementaire alors que la deuxième fournit des LEP recommandées.

En utilisant le facteur d'effet de USEtox, nous avons calculé l'impact potentiel pour un travailleur exposé à 100% de la LEP (OSHA ou de l'ACGIH) sur la totalité de sa vie professionnelle (40 ans, 2000 heures par ans). Au Tableau 2 on peut observer qu'il y a un facteur 30 entre les impacts du tetrachloroéthylène et du dichlorométhane pour une exposition au niveau de la LEP de l'OSHA. Le plus gros écart est un facteur 10 entre les impacts du trichloréthylène et le tetrachloroethylene pour les LEP de l'ACGIH.

Tableau 7-2 : Comparaison des scores d'impacts calculés pour un travailleur exposé à 100% de la Limites d'Exposition Professionnelles tolérés (OSHA et ACGIH) sur la totalité de sa vie professionnelle (40 ans, 2000 heures par ans) pour trois substances basée sur les EF de USEtox

		Trichloréthylène	Tetrachloroéthylène	Dichlorométhane
EF Usetox (cas de cancer/kg pris)		1,72E-03	8,50E-03	1,86E-03
OSHA PEL 8h TWA(mg/m3)[1]		535	670	86,75
ACGIH TLV (mg/m3) [2]		53,5	169,5	173,5
Impact cancer pour une exposition durant 40 ans et 2000 heures, 1,7 m^3/h par ans à une concentration de :	OSHA PEL, exposition 100% du temps de travail (DALY)	1,25E-01	7,75E-01	2,19E-02
	ACGIH TLV, exposition 100% du temps de travail (DALY)	1,25E-02	1,96E-01	4,38E-02

Une deuxième vérification a été effectuée en utilisant l'excès de risque unitaire utilisé par l'OSHA pour développer ses LEP. Il indique l'excès de risque de cancer par unité de concentration de polluant (mg/m^3) pour un individu exposé toute sa vie à ce polluant. Pour prendre en compte le fait que l'exposition professionnelle ne concerne qu'une fraction de la vie du travailleur, l'excès de risque total est mis à l'échelle du temps réel d'exposition en faisant l'hypothèse d'une durée de vie de 70 ans. Dans la Tableau 7-3 il apparait un écart encore plus marqué que pour une exposition au niveau de la LEP de l'OSHA; un facteur 1000 est observé

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[1] Voir https://www.osha.gov/dts/chemicalsampling/toc/toc_chemsamp.html

[2] Voir https://www.osha.gov/dts/chemicalsampling/toc/toc_chemsamp.html

entre l’excès de risque de développement d’un cancer pour une exposition au trichloréthylène ou au dichlorométhane. L’écart est moins marqué, un facteur 50, si l’exposition se fait au niveau de la LEP de l’ACGIH.

Tableau 7-3 : Comparaison des excès de risques basés sur l'excès de risque unitaire pour chaque substance.

	Trichloréthylène	Tetrachloroéthylène	Dichlorométhane
Excès de risque (% point par mg/m3)	1,90E-03	1,90E-04	9,50E-06
Excès de risque pour une exposition à la LED de l’OSHA	13,252%	1,660%	0,011%
Excès de risque pour une exposition à la LED de l’AGCIH	1,325%	0,420%	0,021%

Le but de cette étude sommaire est surtout de montrer des disparités importantes entre les LEP pour différentes substances chimiques. L’explication de ces disparités va bien au-delà du projet de recherche présenté dans cette thèse. Toutefois il serait intéressant de poursuivre une étude plus poussée pour identifier la cause de la différence de classement de dangerosité des substances si on utilise les facteurs d’effet (EF) de USEtox ou les excès de risque unitaires de l’OSHA. De plus, il serait très intéressant d’étudier et comparer de manière plus large les LEP au regard de l’impact potentiel qu’elles considèrent implicitement comme acceptable.

Dans le cas où les limites d’exposition réglementaires seraient utilisées lors du calcul de proxys pour des pays ne publiant pas de données de concentrations de polluants en milieu de travail, il serait important de vérifier la cohérence des limites entre elles au sein d’un même pays. De plus l’existence de limites réglementaires n’entraine pas nécessairement une conformité systématique à celles-ci. Donc si les limites réglementaires sont utilisées pour estimer l'exposition des travailleurs, il faudrait aussi prendre en compte leur mise en application.

CHAPITRE 8: CONCLUSION ET RECOMMANDATIONS

Ce projet de recherche a permis de développer une méthode de caractérisation pour les expositions professionnelles aux polluants (organiques, inorganiques et particules) en analyse des impacts du cycle de vie (AICV), permettant de mettre en lumière les impacts sur les travailleurs des expositions aux polluants en milieu de travail. La méthode développée durant ce projet de recherche permet non seulement de comparer les impacts sur les travailleurs des expositions toxiques aux autres impacts sur la santé humaine à l'échelle du cycle de vie pour une unité fonctionnelle donnée, mais offre aussi un benchmark pour que les industries puissent se comparer à leur moyenne sectorielle. Sur le long terme, le développement de l'utilisation de la méthode AICV pour les prises de décisions permettra de favoriser les industries les plus respectueuses envers l'environnement mais aussi envers leurs travailleurs, poussant vers de meilleures conditions de travail.

Pour ce faire, deux sets de facteurs de caractérisation avec intervalles de confiance sont fournis à deux niveaux d'agrégation : impact par heure travaillée et impact par dollar de production (incluant la chaîne de valeur) soit de manière désagrégée (impact par couple substance-secteur), soit de manière agrégé par secteur ou commodité. De plus cette thèse fournit les outils nécessaires pour de futures mises-à-jour ou une extension à d'autres pays.

La méthode développée est dépendante des données disponibles et malgré un nombre constant de mesures enregistrées dans la base de donnée de l'OSHA, on observe dans les années une diminution du nombre de substances pour lesquelles à la fois un facteur d'effet est fourni par USEtox et des concentrations en milieu professionnel sont disponibles. Si cette tendance se poursuit, la mise à jour des CF pourrait devenir problématique. L'extension à d'autres substances chimique est tributaire du développement de nouveaux facteurs d'effets, mais cela signifie qu'il faut réaliser un effort de recherche pour identifier les données pertinentes issues d'autres bases de données (telle que celle de REACH) ou ultimement produire ces données sous la forme d'étude toxicologies (longues et coûteuses). L'utilisation de nouvelles bases de données telle que celle de REACH semble la meilleure avenue de recherche en ce moment.

Une limitation de la méthode développée pour estimer les impacts issus des expositions en milieu de travail dans les chaines d'approvisionnement est relative à l'hypothèse simplificatrice selon laquelle les produits importés sont considérés comme produits sur le territoire des États-Unis, négligeant alors les différences d'impacts liées à la production dans un autre pays. Pour améliorer cette modélisation et prendre en compte une chaîne de valeur internationale, l'identification d'un modèle IO multinational est nécessaire (tel que EORA Worldmrio ou Exiobase), mais pas suffisante. Pour chaque pays couvert par le modèle input-output il faut un set de CF et donc une base de concentration de polluants en milieu de travail. À partir du moment où plusieurs bases sont utilisées il faudra analyser la cohérence de ces données : la concentration de polluants en milieu de travail mesurées et rendues disponibles dans ces bases sont généralement effectuée par une agence gouvernementale ou requise par la réglementation en place. Or les réglementations varient beaucoup entre les pays et un travail d'uniformisation sera nécessaire.

Finalement, il est important de noter que ce projet de recherche n'est qu'un premier pas : la problématique des impacts sur la santé des travailleurs ne se résume pas à l'exposition à des substances chimiques. Les accidents de travails, l'ergonomie des postes de travail, les accidents de trajets et le stress au travail ne sont que quelques-unes des causes d'impacts sur la santé des travailleurs. La méthode développée ici n'est qu'un pas dans le sens de l'intégration des impacts sur les travailleurs en AICV, mais un pas important qui s'inscrit dans un effort de recherche partagé par plusieurs équipes de recherche.

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ANNEXE A - INFORMATIONS SUPPLÉMENTAIRES POUR L'ARTICLE PRÉSENTÉ AU CHAPITRE 2

Table A.1 : List of case studies, blue lines are using *impact-based* method, white are using *hazard-based* methods and purple use a method that is both *impact-based* and *hazard-based*.

Authors	Title	Hazard covered	Damage covered	Cause-to-effect chain steps covered				Life cycle phases covered
				Hazard	Risk	Effect	Impact	
Socolof et *al.* 2001	Desktop Computer Displays: A Life-Cycle Assessment (Volume 1); EPA 744-R-01-004a	Chem (inhalation)	cancer, non-cancer	1	0	1	0	full
Schmidt et *al.* 2004	A comparative Life Cycle Assessment of Building Insulation Products made of Stone Wool, Paper Wool and Flax, Part 1 and 2	Chem (inhalation)	no impact assessment	1	1	0	0	manufacture only
Schmidt et *al.* 2004	LCA and the working environment	all (depend on available data)	no impact assessment	0	0	1	0	full
Hellweg et *al.* 2005	Confronting workplace exposure to chemicals with LCA: examples of trichloroethylene and perchloroethylene in metal degreasing and dry cleaning	Chem (inhalation)	no impact assessment	1	1	0	0	Manufacture (one activity)
Geibig et *al.* 2005	Solders in Electronics: A Life-Cycle Assessment; EPA 744-R-05-001	Chem (inhalation)	cancer, non-cancer	1	0	1	0	full
Koneczny et *al.* 2007	Environmental Assessment of Municipal Waste Management Scenarios: Part II – Detailed Life Cycle Assessments	all (depend on available data)	all (depend on available data)	0	0	1	1	full
Pettersen et *al.* 2008	Occupational health impacts: offshore crane lifts in life cycle assessment	Mechanical	all (depend on available data)	0	0	1	1	Manufacture (one activity)
Socolof et *al.* 2008	Wire and Cable Insulation and Jacketing: Life-Cycle Assessments for Selected Applications; EPA 744-R-08-001	Chem (inhalation)	cancer, non-cancer	1	0	1	0	full
Kikuchi et *al.* 2008	Practical Method of Assessing Local and Global Impacts for Risk-Based Decision Making: A Case Study of Metal Degreasing Processes	Chem (inhalation)	no impact assessment	1	1	1	1	Manufacture (one activity)
Demou et *al.* 2009	Evaluating indoor exposure modeling alternatives for LCA: a case study in the vehicle repair industry	Chem (inhalation)	no impact assessment	1	1	0	0	Manufacture (one activity)
Huuskonen, 2012	Inclusion of occupational safety in life cycle assessment	all (depend on available data)	all (depend on available data)	0	0	1	1	full

Table A.1 : List of case studies, blue lines are using impact-based method, white are using *hazard-based* methods and purple use a method that is both *impact-based* and *hazard-based* (cont. and end)

Authors	Title	Hazard covered	Damage covered	Cause-to-effect chain steps covered				Life cycle phases covered
				Hazard	Risk	Effect	Impact	
Amarakoon et *al*. 2013	Application of Life-Cycle Assessment to Nanoscale Technology: Lithium-ion Batteries for Electric Vehicles; EPA 744-R-12-001	Chem (inhalation)	cancer, non-cancer	1	0	1	0	full
Walser et *al*. 2013	Indoor Exposure to Toluene from Printed Matter Matters: Complementary Views from Life Cycle Assessment and Risk Assessment	Chem (inhalation)	cases	1	1	1	0	Manufacture (one activity)
Scanlon et *al*. 2013	The work environment disability-adjusted life	all (depend on available data)	all (depend on available data)	0	0	1	1	full
Golsteijn et *al*. 2014	Including exposure variability in the life cycle impact assessment of indoor emissions: The case of metal degreasing	Chem (inhalation)	cases, DALY	1	1	1	0	Manufacture (one activity)
Tong et *al*. 2014	An LCA-based health damage evaluation method for coal mine dust (in Progress in Mine Safety Science and Engineering II, He et al. (ed.))	Chem (inhalation)	cases, DALY	1	1	1	1	Manufacture (one activity)
Kikuchi et *al*. 2014	Design of recycling system for poly(methyl methacrylate) (PMMA). Part 2: process hazards and material flow analysis	Chem (inhalation)	no impact assessment	1	0	0	0	Manufacture (one activity)
Kijko et *al*. 2016	Occupational health impacts of organic chemical exposure: the product life cycle perspective	Chem (inhalation)	cancer, non-cancer	1	1	1	1	full
Hosseinijou et *al*. 2014	Social life cycle assessment for material selection: a case study of building materials	all (depend on available data)	no impact assessment	1	1	1	0	specific phases (identified with MFA)
Benoit Norris et *al*. 2014	Efficient assessment of social hotspots in the supply chains of 100 product categories using the Social Hotspots Database	Psychological	no impact assessment	1	1	0	0	full

ANNEXE B INFORMATIONS SUPPLÉMENTAIRES POUR L'ARTICLE PRÉSENTÉ AU CHAPITRE 5

Table B.1 : Filtering criteria for raw concentrations

Field	Description	Possible values	Filtered values
inspection_number	Description: Unique identifier tied to inspection	Nine numbers in length	All
establishment_name	Sampled establishment		All
City	Identifies the site city in which the inspection was carried out		All
State	Identifies the site state in which the inspection was carried out		All
zip_code	Identifies the site zip code in which the inspection was carried out		All
sic_code	Indicates the 4-digit Standard Industrial Classification Code from the 1987 version of the SIC manual that most closely applies See http://www.osha.gov/pls/imis/sicsearch.html.	4-digit code	All that refers to a sector 3 NAICS 2007 sector

Table B.1 : Filtering criteria for raw concentrations (cont.)

naics_code	North American Industrial Classification System Code See http://www.census.gov/epcd/naics02/.	6-digit code	All starting with a 3
sampling_number	Unique identifier tied to single exposure assessment There may be multiple media tied to this number, reflecting multiple samples in the time-weighted sample.		All
office_id	Unique number assigned to an OSHA Office		All
date_sampled	Date on which the sample was taken		01/01/2002 to 31/12/2009
date_reported	Date on which the results were released by the OSHA		All
eight_hour_twa_calc	Based on eight-hour TWA calculation	Y, N	All
instrument_type	Type of laboratory instrument used in the analysis		All
lab_number	Unique identifier assigned by laboratory for internal use	5 digits followed by a letter	All

Table B.1 : Filtering criteria for raw concentrations (cont.)

field_number	Unique identifier tied to individual sample media submitted for analysis		All
sample_type	Sample type	P: Personal; A: Area; B: Bulk W: Wipe	P
blank_used	Sample represents a blank used for analysis	Y, N	N
time_sampled	Time sampled in minutes		All
air_volume_sampled	Air volume sampled in litres		All
sample_weight	Sample weight for bulks and silica samples		All
imis_substance_code	The IMIS substance code number is the substance code assigned by OSHA to each substance. See OSHA Chemical Sampling Information at http://www.osha.gov/dts/chemicalsampling/toc/field.html.	4-digit code	All corresponding to organic chemicals covered by USETOX database: www.usetox.org/model/download/usetox

Table B.1 : Filtering criteria for raw concentrations (cont. and end)

substance	Substances are primarily listed by chemical name, as they appear in the OSHA PELs, 29 CFR 1910.1000, TABLES Z-1-A, Z-2, Z-3; the ACGIH TLV's or by common name.		All
sample_result	Sample result from laboratory analysis for each sample submitted with a unique field number Note: Multiple media integrated samples can be tied to a single sampling number		All
unit_of_measurement	Unit of measurement (UOM) from IMIS manual	M: mg/m3 X: Micrograms P: Parts per million Y: Milligrams F: Fibres/cc %: Percentage	P, M, X or Y

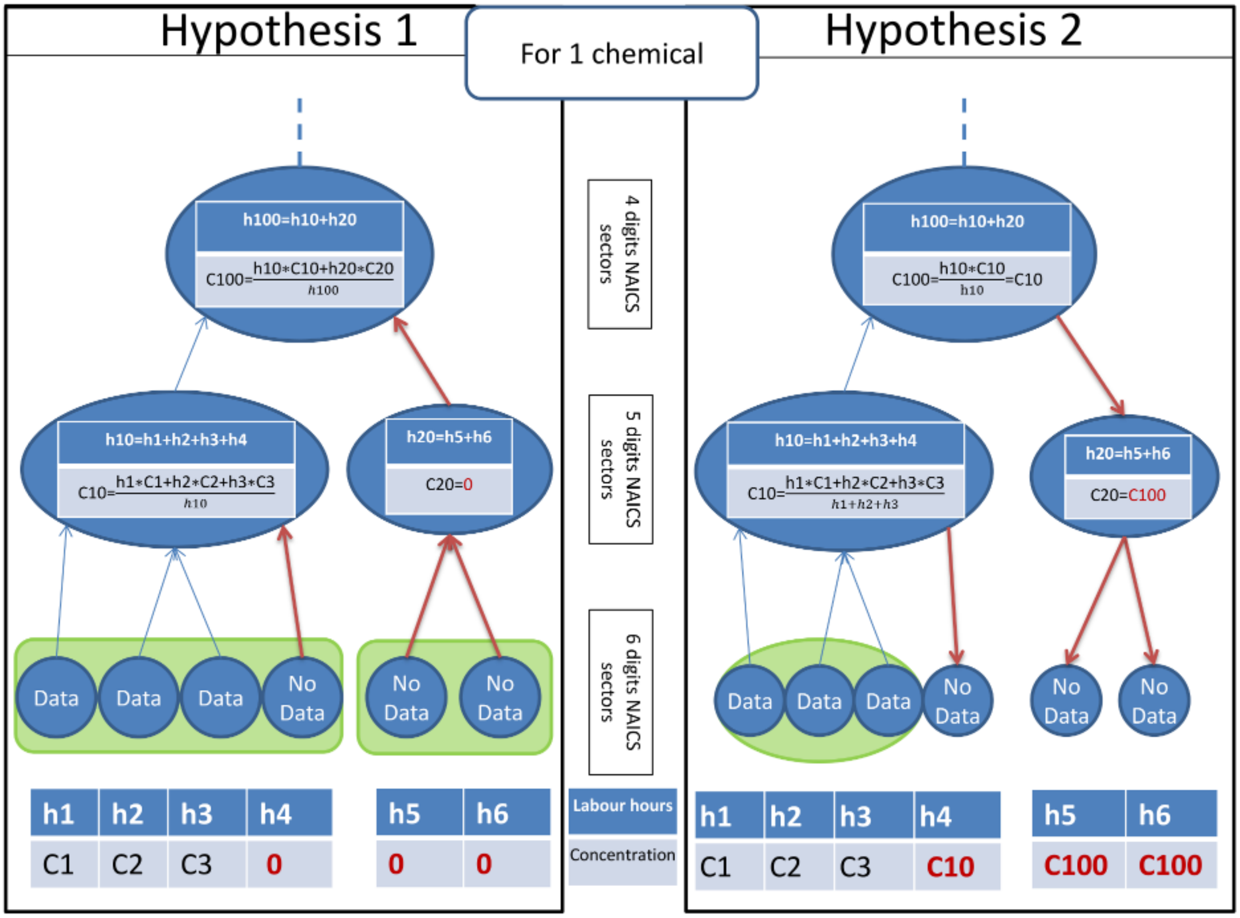


Figure B.1: Two methods to determine the concentrations

Table B.2 : Comparison of OSHA measured concentrations with IARC monograph reviews

Substance	Concentration range reported in the IARC monograph (mg/m3)	Measured concentration range (mg/m3)	Reference
Styrene	8; 900	0; 900	IARC monographs volume 82
Tetrachloroethylene	0; 30000	0; 200	IARC monographs volume 63
Formaldehyde	0; 10	0; 7	ARC monographs volume 88
Dichloromethane/Methylene chloride	7; 2000	0; 3000	IARC monographs volume 71
Trichloroethylene	200 (arithmetic mean across all sectors)	0; 1,7000	IARC monographs volume 63
Ethylbenzene	0; 1,900	0; 200	IARC monographs volume 77
Methyl methacrylate	0; 47	0; 180	IARC monographs volume 60

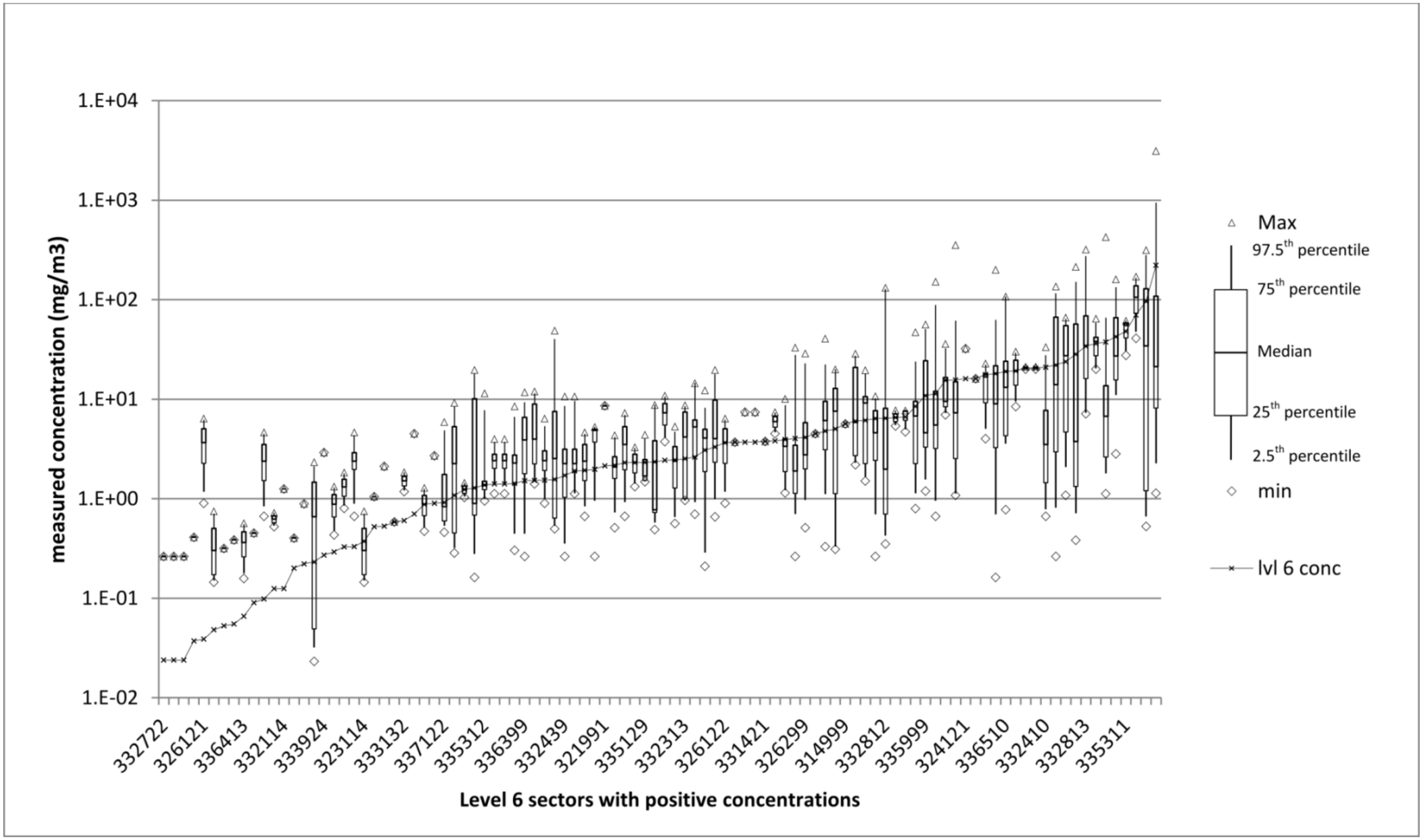


Figure B.2: Measured concentrations of ethylbenzene grouped at level 6

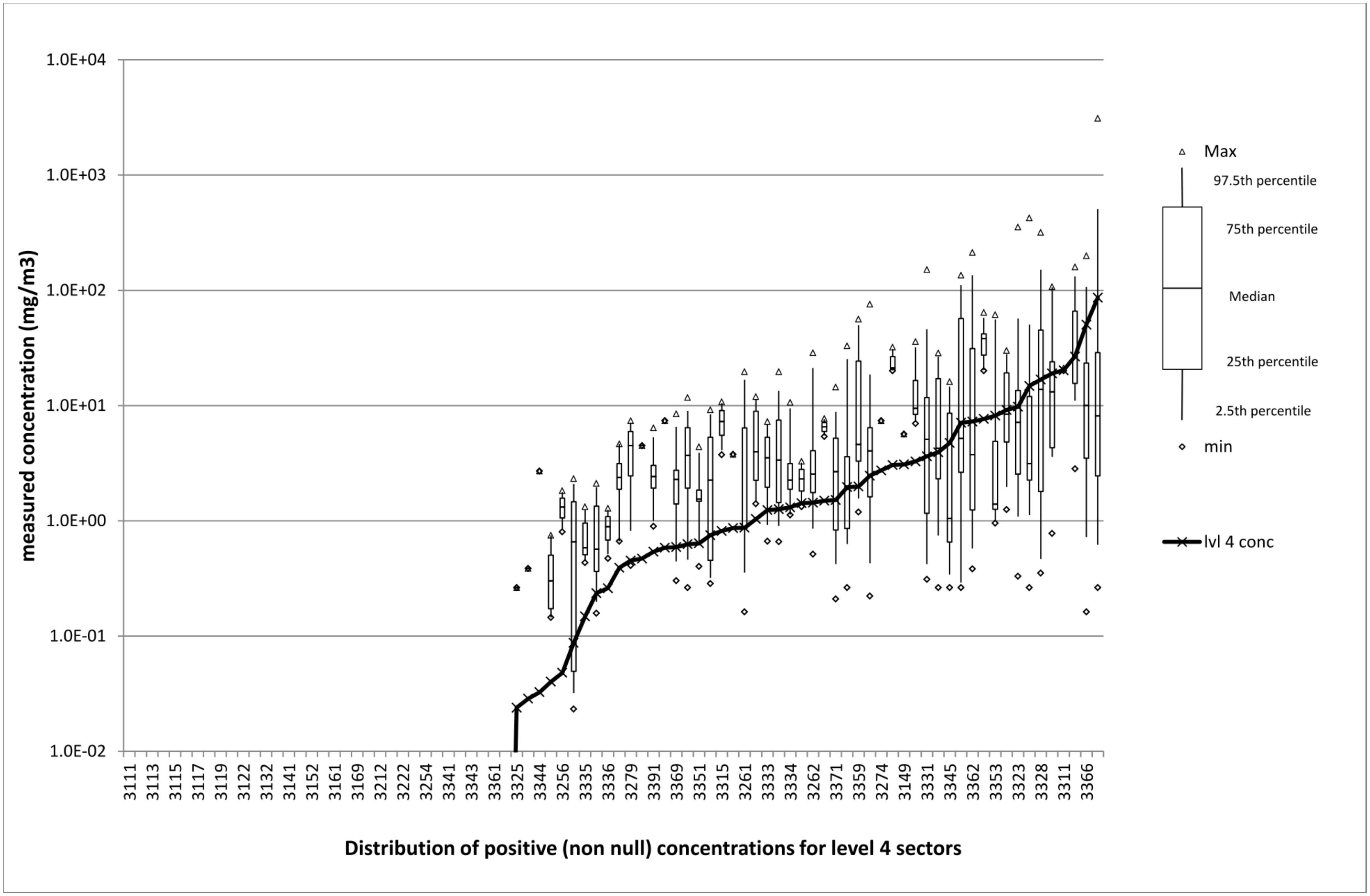


Figure B.3: Measured concentrations of ethylbenzene grouped at level 4

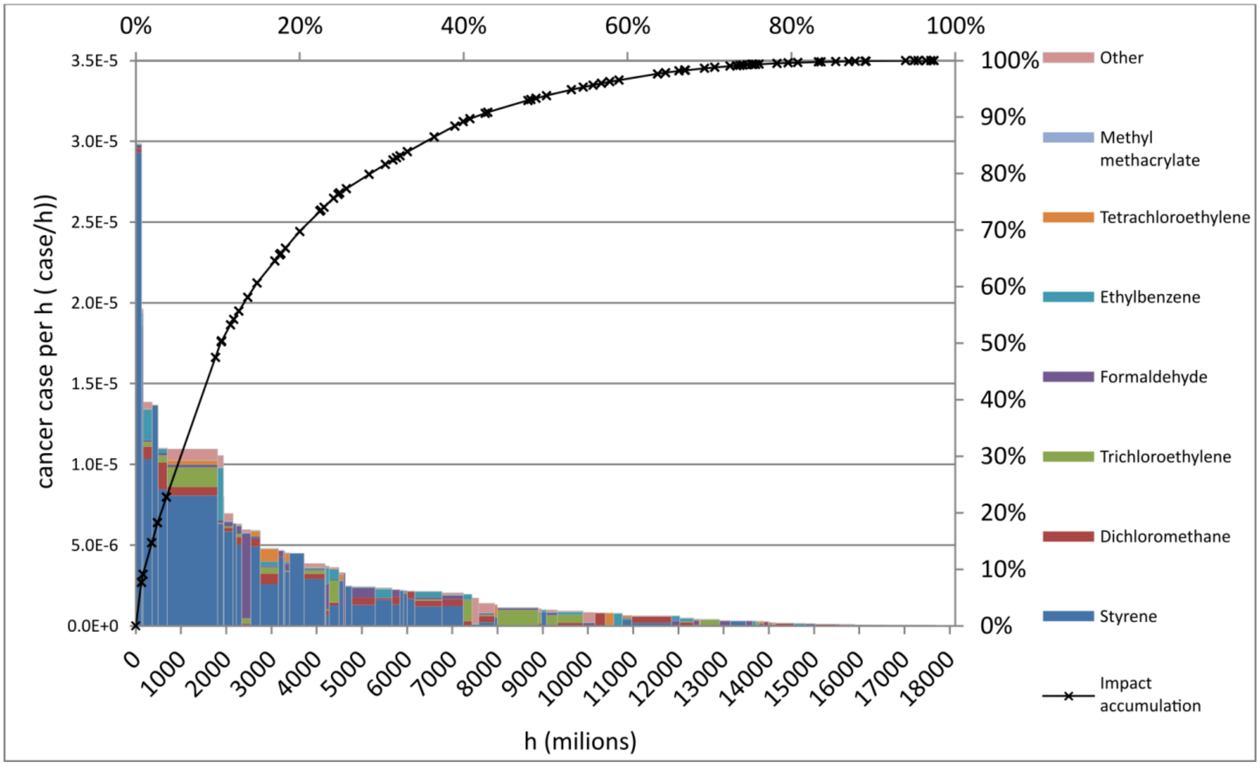


Figure B.4: Cancer cases per hour as a function of labour hours at level 4, sorted by cancer cases per h

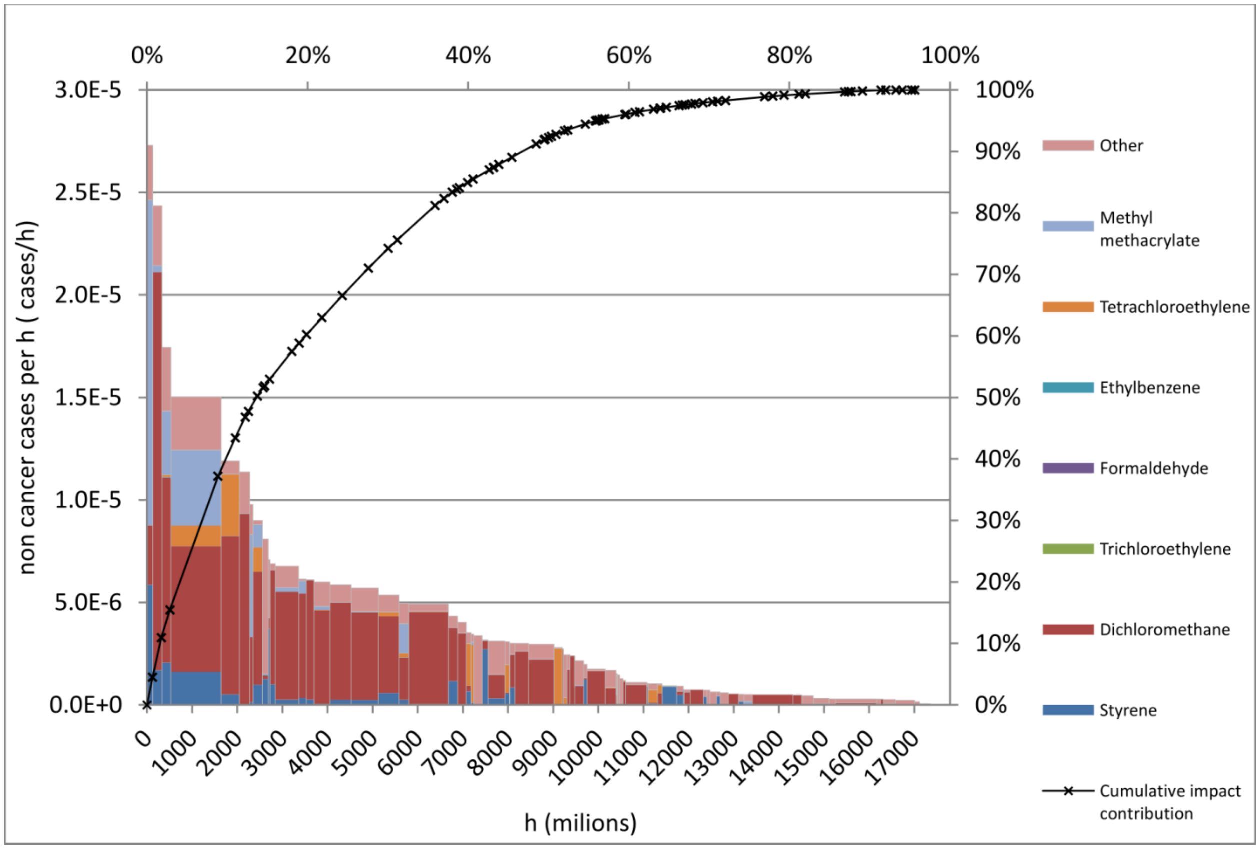


Figure B.5: Non-cancer cases per hour as a function of labour hour at level 4, sorted by non-cancer cases per h

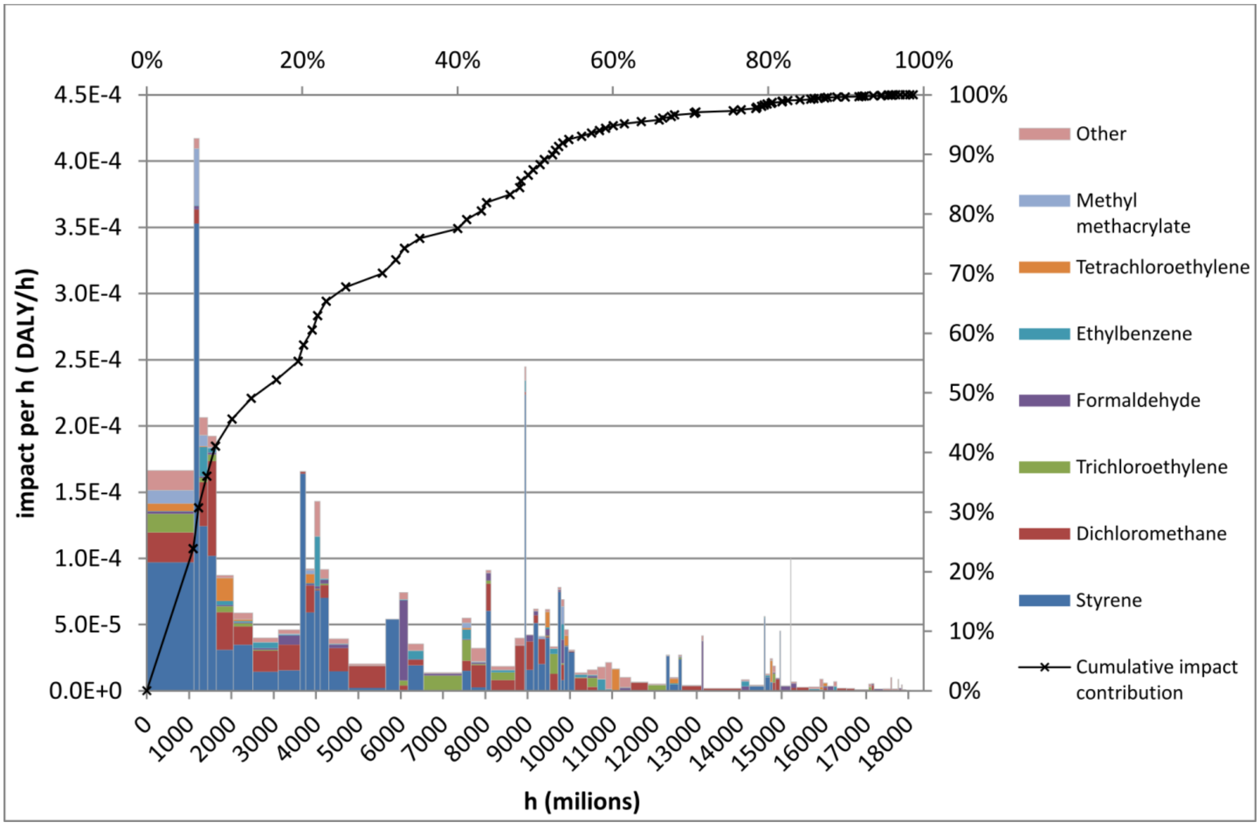


Figure B.6: Impact per hour as a function of labour hours at level 4, sorted by area (i.e. total impact)

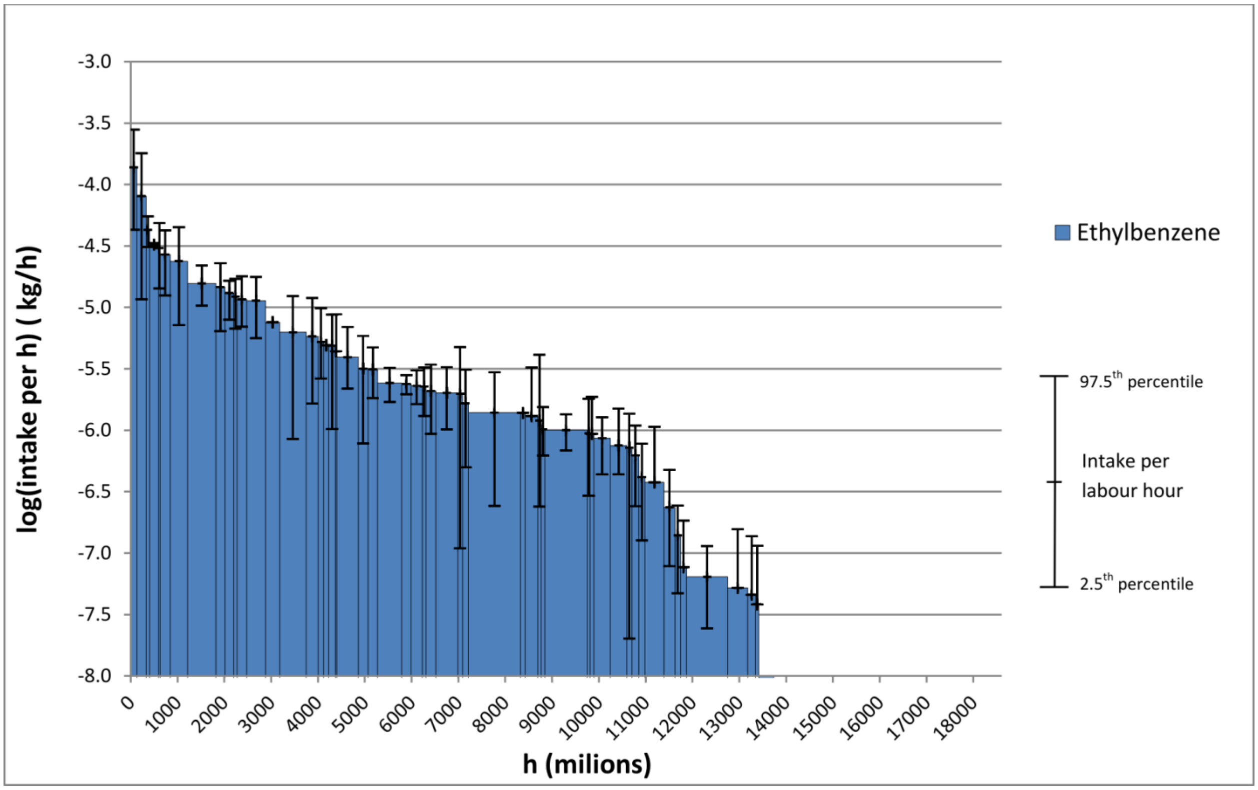


Figure B.7: Intake per h for ethyl-benzene with uncertainty bars as a function of labour hours at level 4, sorted by intake per h (i.e. intake intensity)

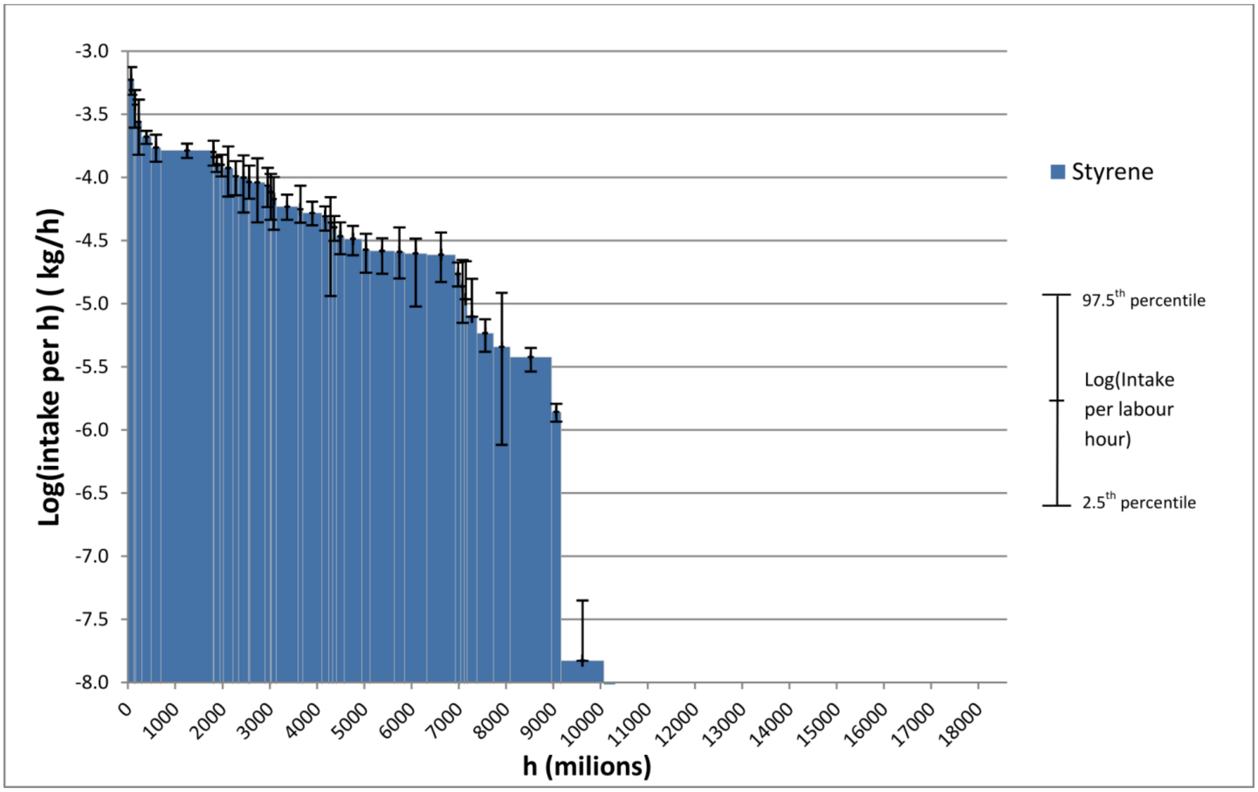


Figure B.8: Intake per h for styrene with uncertainty bars as a function of labour hours at level 4, sorted by intake per h (i.e. intake intensity)

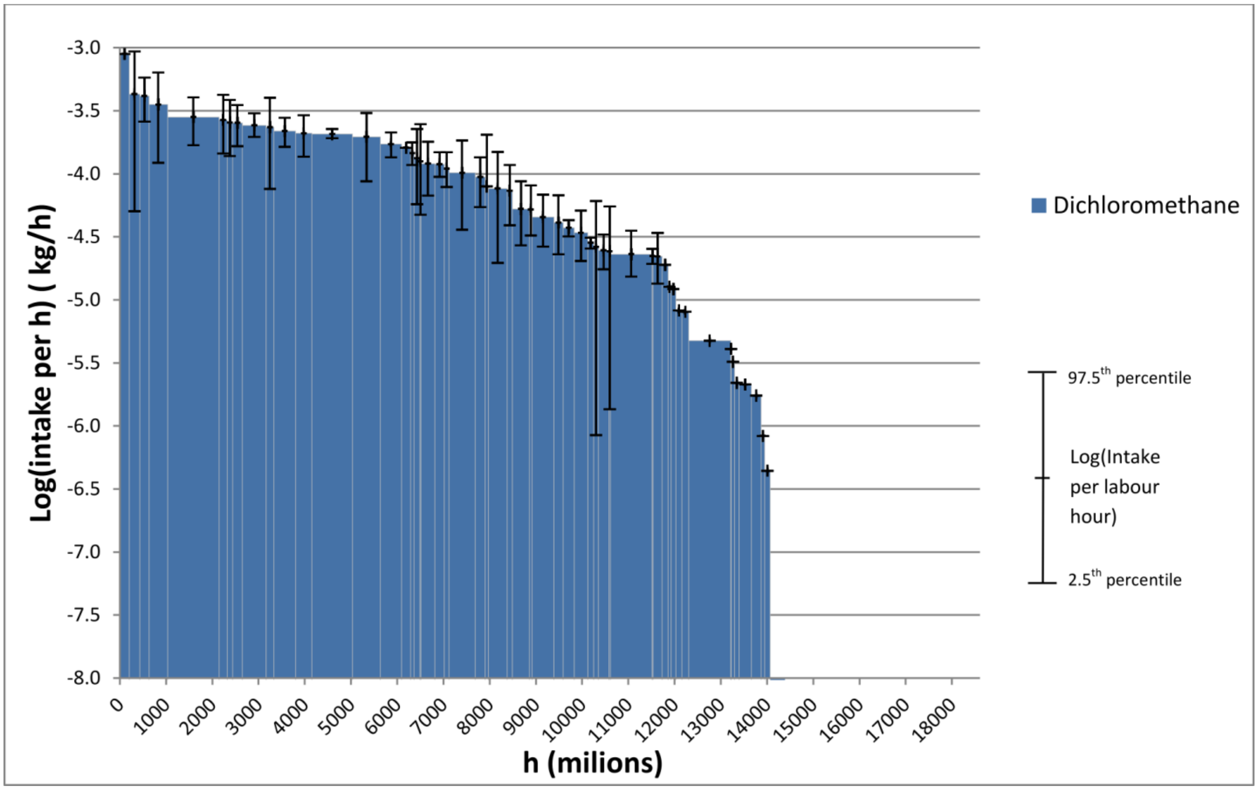


Figure B.9: Intake per h for dichloromethane with uncertainty bars as a function of labour hours at level 4, sorted by intake per h (i.e. intake intensity)

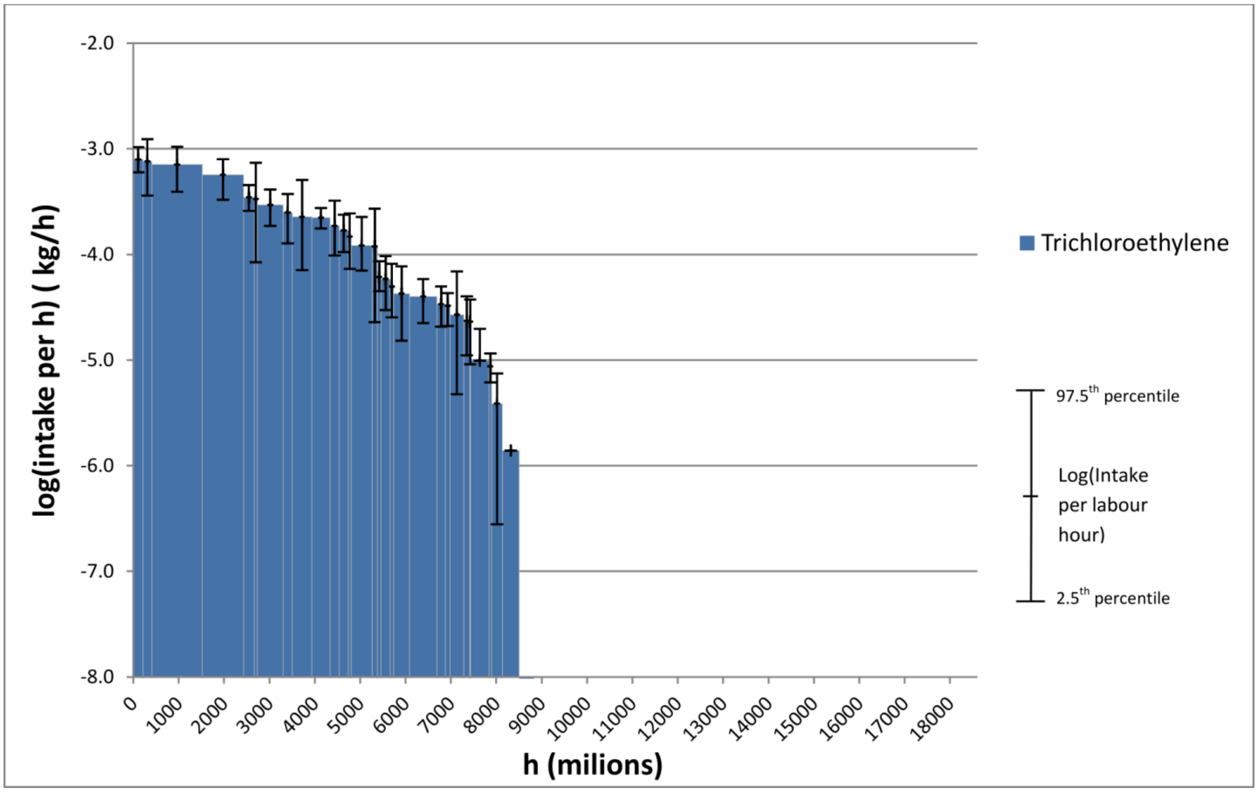


Figure B.10: Intake per h for trichloroethylene with uncertainty bars as a function of labour hours at level 4, sorted by intake per h (i.e. intake intensity)

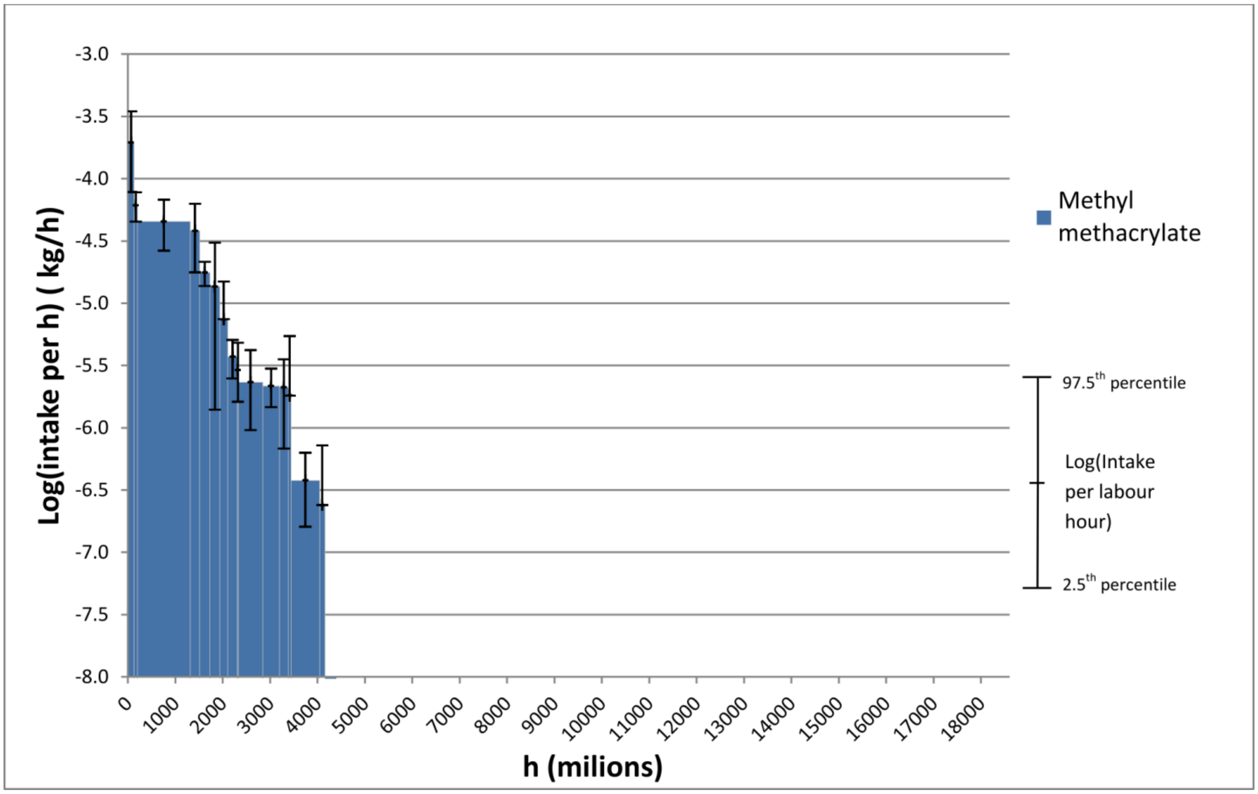


Figure B.11: Intake per h for methyl-methacrylate with uncertainty bars as a function of labour hours at level 4, sorted by intake per h (i.e. intake intensity)

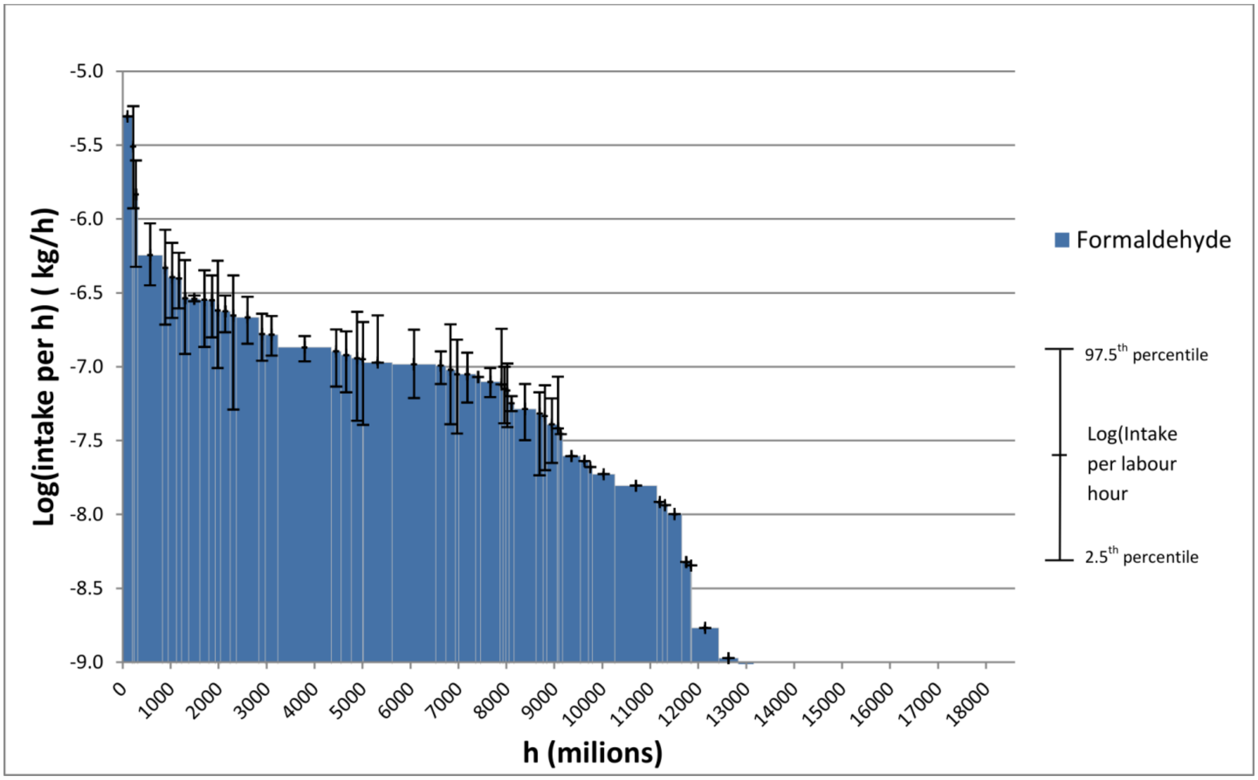


Figure B.12: Intake per h for formaldehyde with uncertainty bars as a function of labour hours at level 4, sorted by intake per h (i.e. intake intensity)

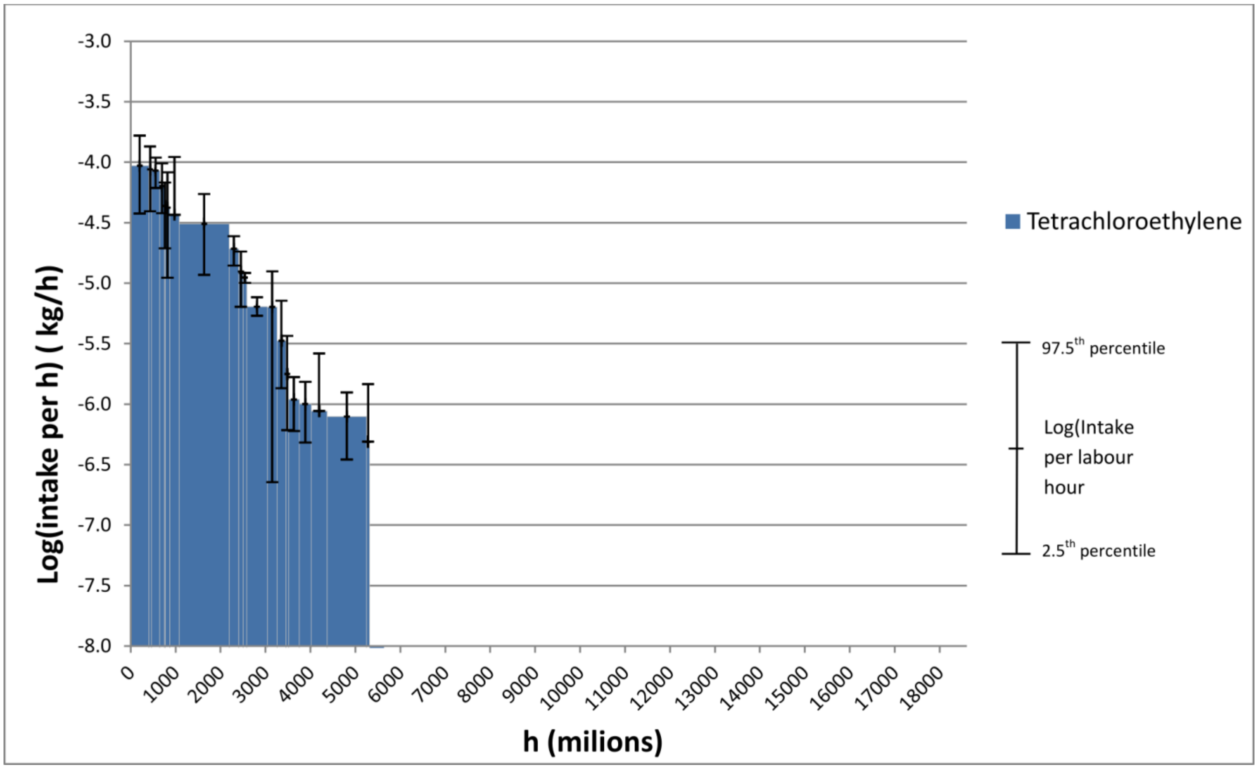
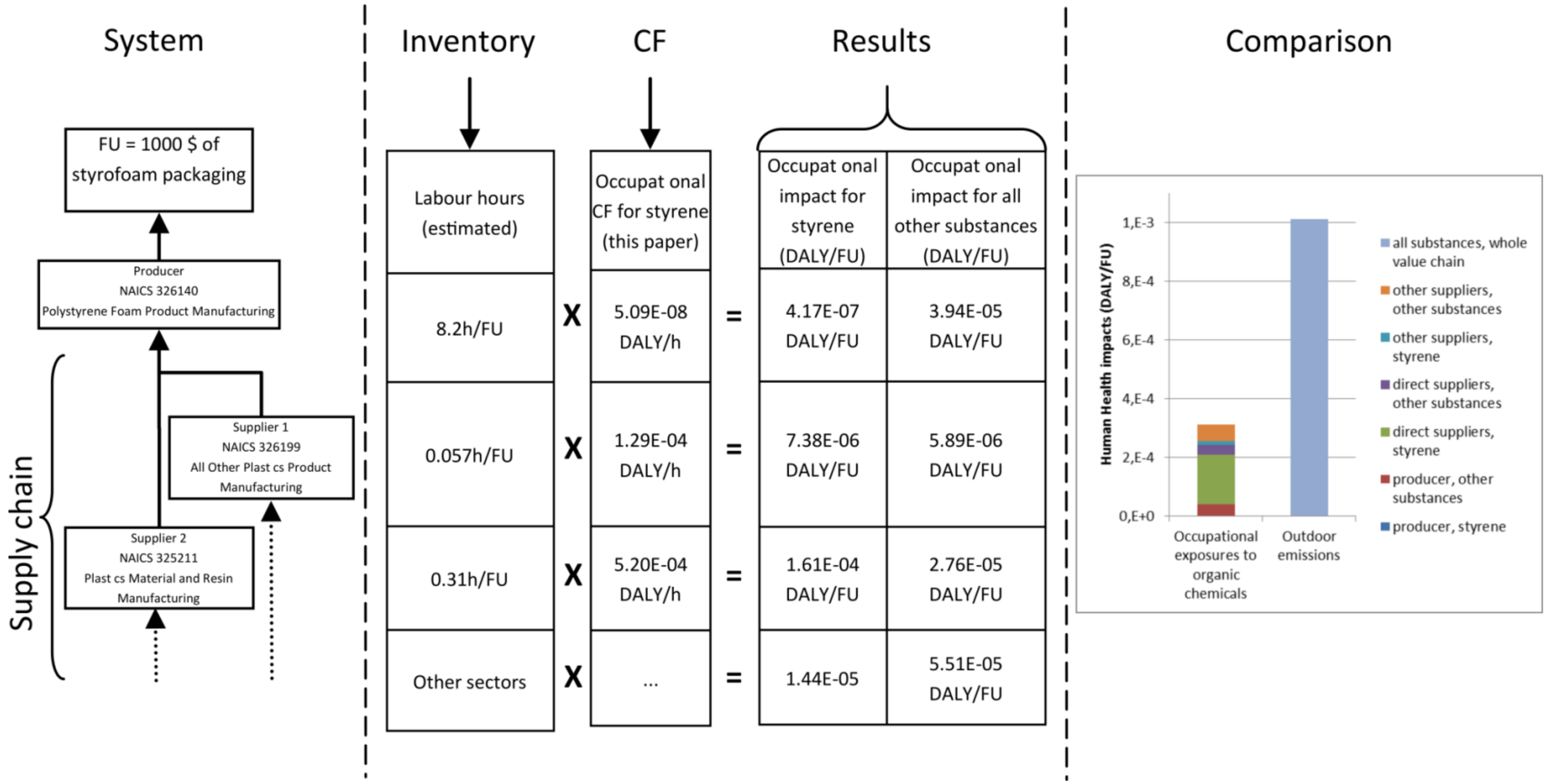


Figure B.13: Intake per h for tetrachloroethylene with uncertainty bars as a function of labour hours at level 4, sorted by intake per h (i.e. intake intensity)



Labour hours (estimated)		Occupational CF for styrene (this paper)		Occupational impact for styrene (DALY/FU)	Occupational impact for all other substances (DALY/FU)
8.2h/FU	X	5.09E-08 DALY/h	=	4.17E-07 DALY/FU	3.94E-05 DALY/FU
0.057h/FU	X	1.29E-04 DALY/h	=	7.38E-06 DALY/FU	5.89E-06 DALY/FU
0.31h/FU	X	5.20E-04 DALY/h	=	1.61E-04 DALY/FU	2.76E-05 DALY/FU
Other sectors	X	...	=	1.44E-05	5.51E-05 DALY/FU

Figure B.14 Occupational health impacts per 1000$ of Styrofoam packaging. Description of the system, labours hours worked per functional unit, Cf for styrene and occupational impacts for styrene and all other substances.

Figure B.14 presents a case study demonstrating the use of the CF provided by the article. The functional unit is 1000$ of production from the 326140 Polystyrene Foam Product Manufacturing sector.

Cumulated life cycle spending in $ per functional unit (FU) were extracted for the producer sector, the two direct suppliers 1 and 2, and for all other sectors, using the Simapro software with CEDA database (version 4). Combining these cumulated spending with the labour hours per $ in each sector, we first calculate the inventory data expressed in labour hours worked in each sector per FU. The number of hours worked per FU is more than ten times higher in the main producer sector than in each of the supplier sector.

We then multiply these labour hours per functional unit by the corresponding CFs provided for each sector in the present paper (styrene CF provided in the CF column) to obtain the impact per FU in each sector. Looking first at the impact of styrene, the impact in the producer manufacturing sector with the largest number of hours (Polystyrene Foam Product Manufacturing), is more than 300 times smaller than the impact in supplier's 2 sector (Plastic material and resin manufacturing), which represent more than 50% of the overall impact considering all other sectors and substances (Total occupational impact of 3.1×10^{-4} DALY/FU).

This short example demonstrates how the provided CF enable the practitioner to easily obtain the impact, either detailed by substance or aggregated. It also shows the importance to not only consider the impact in the main producer sector but to evaluate impacts over the entire supply chain, thus the interest of the characterization factors provided in the present paper for each sector of the entire industry.

As CEDA also provides outdoor emission data per production $ for each sector, we can compare the occupational health impacts due to exposure to organic chemicals with the impacts on human health due to outdoor emission (comparison graph on the right of Figure B.4), the two impacts being within a factor 5.

In addition to the impacts presented in this example, the same analysis can be easily performed at the intake level since the intake intensity factors are also provided for each chemical-sector couple.

ANNEXE C INFORMATIONS SUPPLÉMENTAIRES POUR L'ARTICLE PRÉSENTÉ AU CHAPITRE 6

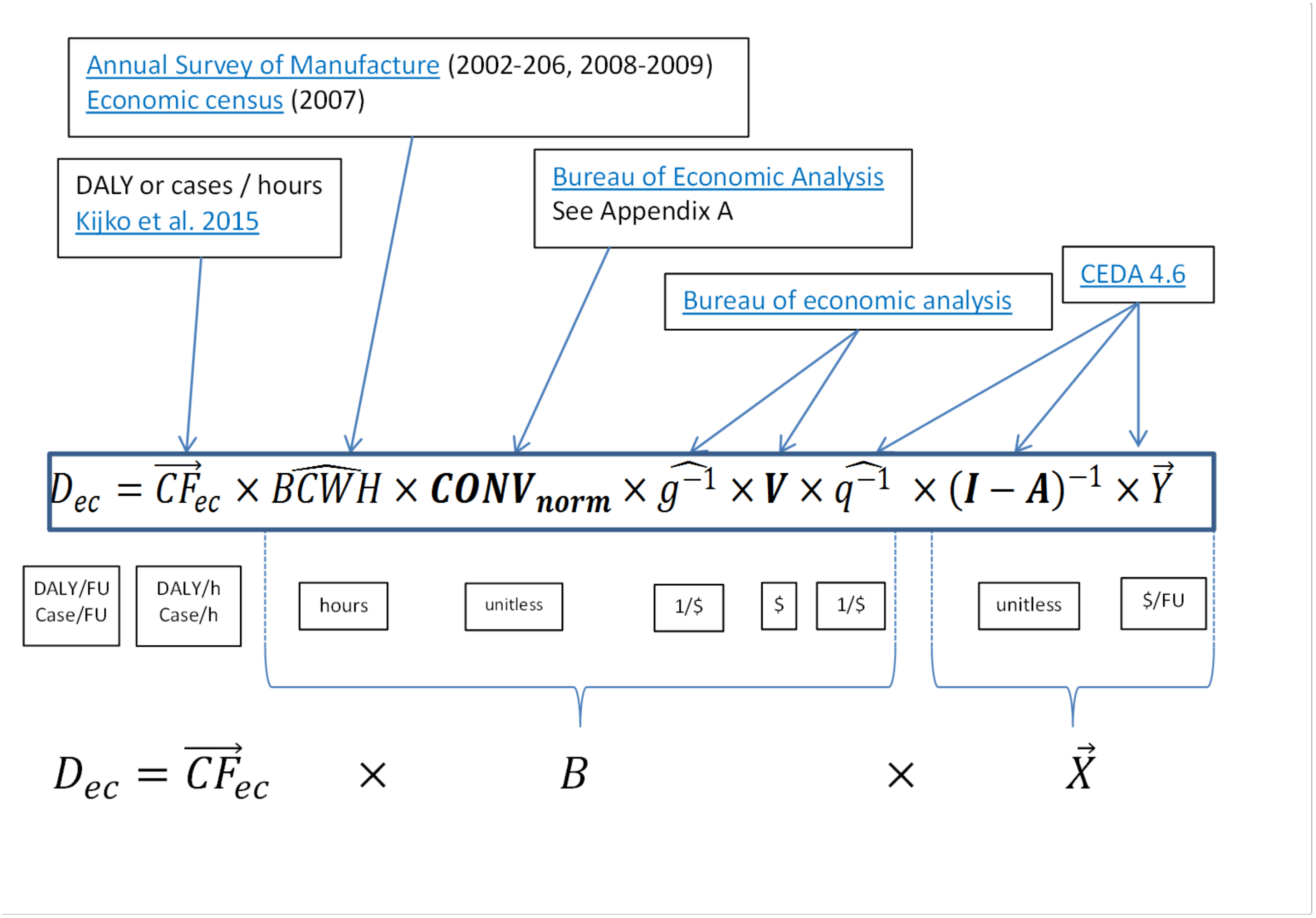


Figure C.1: Data source

SI-1: DAMAGE IN EACH IO/NAICS SECTORS

The following describes how to obtain detailed dollar based impact intensities due to the different IO commodities in (or NAICS sectors) for the different components of the FU.

Equation 6.4 define D_{ec}

$$D_{ec} = \overrightarrow{CF}_{ec} \times \vec{h} = \overrightarrow{CF}_{ec} \times \boldsymbol{B} \times \vec{X} = \overrightarrow{CF}_{ec} \times \boldsymbol{B} \times (\boldsymbol{I} - \boldsymbol{A})^{-1} \times \vec{Y} \tag{S1}$$

Or in another symbolism:

$$D_{ec} = \begin{bmatrix} \ldots & \overrightarrow{CF}_{ec} & \ldots \end{bmatrix} \times \begin{bmatrix} \ldots \\ \vec{h} \\ \ldots \end{bmatrix} \tag{S2}$$

$$D_{ec} = \begin{bmatrix} \ldots & \overrightarrow{CF}_{ec} & \ldots \end{bmatrix} \times [\boldsymbol{B}] \times \begin{bmatrix} \ldots \\ \vec{X} \\ \ldots \end{bmatrix} \tag{S3}$$

$$D_{ec} = \begin{bmatrix} \ldots & \overrightarrow{CF}_{ec} & \ldots \end{bmatrix} \times [\boldsymbol{B}] \times ([\boldsymbol{I}] - [\boldsymbol{A}])^{-1} \times \begin{bmatrix} \ldots \\ \vec{Y} \\ \ldots \end{bmatrix} \tag{S4}$$

If we use a diagonal matrix instead of the CF vector, we will obtain a damage vector providing the total impact (value chain + manufacturing sector) per FU in each of the NAICS sectors:

$$\begin{bmatrix} \ldots \\ \overrightarrow{D_{ec}} \\ \ldots \end{bmatrix} = \left[\widehat{\overrightarrow{CF_{ec}}}\right] \times [\boldsymbol{B}] \times ([\boldsymbol{I}] - [\boldsymbol{A}])^{-1} \times \begin{bmatrix} \ldots \\ \vec{Y} \\ \ldots \end{bmatrix} \tag{S5}$$

The notation $\widehat{\overrightarrow{CF_{ec}}}$ corresponds to a diagonal matrix with the elements of $\overrightarrow{CF_{ec}}$ on the diagonal and 0 outside of the diagonal.

Alternatively, by using a diagonal matrix instead of the result of $\begin{bmatrix} \ldots & \overrightarrow{CF}_{ec} & \ldots \end{bmatrix} \times [\boldsymbol{B}]$ we will obtain a damage vector providing the total impact (value chain + manufacturing sector) per FU in each of the IO sectors:

$$\begin{bmatrix} \ldots \\ \overrightarrow{D_{ec}} \\ \ldots \end{bmatrix} = \left[\widehat{\overrightarrow{CF_{ec}} \times [\boldsymbol{B}]}\right] \times ([\boldsymbol{I}] - [\boldsymbol{A}])^{-1} \times \begin{bmatrix} \ldots \\ \vec{Y} \\ \ldots \end{bmatrix} \tag{S6}$$

Also, using a diagonal matrix instead of the $\begin{bmatrix} \cdots \\ \vec{Y} \\ \cdots \end{bmatrix}$ vector will help differentiate between the impacts due the different component of the $\begin{bmatrix} \cdots \\ \vec{Y} \\ \cdots \end{bmatrix}$ vector. For instance if the purchases per functional units come from different sectors, or if the functional unit is the production of a manufactured good (in which case, the component of the $\begin{bmatrix} \cdots \\ \vec{Y} \\ \cdots \end{bmatrix}$ vector would be the purchases per FU from each supplier sector, as in the illustrative case study, see table B.2).

In those cases one can obtain a matrix of dollar based impact intensities providing the damage due to each IO commodity (respectively NAICS sector) as rows with each component of the FU (columns) by using Equation S7 (respectively S8):

$$[\boldsymbol{D}_{ec}] = \left[\widehat{\overrightarrow{CF_{ec}}}\right] \times [\boldsymbol{B}] \times ([\boldsymbol{I}] - [\boldsymbol{A}])^{-1} \times \left[\hat{\vec{Y}}\right] \tag{S7}$$

$$[\boldsymbol{D}_{ec}] = \left[\widehat{\overrightarrow{CF_{ec}} \times [\boldsymbol{B}]}\right] \times ([\boldsymbol{I}] - [\boldsymbol{A}])^{-1} \times \left[\hat{\vec{Y}}\right] \tag{S8}$$

SI-2: DAMAGE AT MANUFACTURING FACILITY, IN THE SUPPLY CHAIN

Eq 3. Defines the total impact (supply chain + manufacturing facility). But one might want to differentiate between the supply chain and the manufacturing facility.

It must be noted that with $\vec{Y}$ the vector containing the \$/FU of demand (such as the price of the chair in our illustrative case study), the IO model can be modified as follow:

$$Total\ demand = (\boldsymbol{I}-\boldsymbol{A})^{-1}\times\vec{Y} = \vec{Y} + ((\boldsymbol{I}-\boldsymbol{A})^{-1} - I)\times\vec{Y} \tag{S9}$$

And using the power serie law: $(\boldsymbol{I}-\boldsymbol{A})^{-1} = \sum_{n=0}^{n\to\infty}\boldsymbol{A}^{n}$ (S10)

We then have: $Total\ demand = \vec{Y} + ((\sum_{n=0}^{n\to\infty}\boldsymbol{A}^{n}) - I)\times\vec{Y} = \vec{Y} + (\sum_{n=1}^{n\to\infty}\boldsymbol{A}^{n})\times\vec{P}$ (S11)

$$Total\ demand = \vec{Y} + (\sum_{n=1}^{n\to\infty}\boldsymbol{A}^{n-1})\times\boldsymbol{A}\times\vec{Y} = \vec{Y} + (\sum_{n=0}^{n\to\infty}\boldsymbol{A}^{n})\times\boldsymbol{A}\times\vec{Y} \tag{S12}$$

$$Total\ demand = \vec{Y} + (\boldsymbol{I}-\boldsymbol{A})^{-1}\times\boldsymbol{A}\times\vec{Y} \tag{S13}$$

It is interesting to note that $\boldsymbol{A}\times\vec{Y}$ is the direct requirement of the demand vector $\vec{Y}$. If we see $\vec{Y}$ as the value of a product, or the demand per FU to the manufacturer of this product, then $\boldsymbol{A}\times\vec{Y}$ is the demand per FU to the suppliers of the product manufacturer. Eq 13 shows that the total demand is the sum of the demand per FU to the manufacturer plus the total demand linked to the demand to the suppliers of the product manufacturer.

Joining Eq S13 and Eq 3:

$$D_{ec} = \overrightarrow{CF}_{ec}\times\boldsymbol{B}\times\vec{Y} + \overrightarrow{CF}_{ec}\times\boldsymbol{B}\times(\boldsymbol{I}-\boldsymbol{A})^{-1}\times\boldsymbol{A}\times\vec{Y} = \overrightarrow{CF2}_{ec}\times\vec{Y} \tag{S14}$$

$$Damage\ at\ manufacturing\ facility_{ec} = \overrightarrow{CF}_{ec}\times\boldsymbol{B}\times\vec{Y} = \overrightarrow{CF2\_manufact}_{ec}\times\vec{Y} \tag{S15}$$

$\overrightarrow{CF2\_manufact}_{ec}$ are provided in the SI.slsx file in the “CF by sector” sheet as Direct .

$$Damage\ in\ supply\ chain_{ec} = \overrightarrow{CF2}_{ec}\times\vec{Y} - \overrightarrow{CF2\_manufact}_{ec}\times\vec{Y} \tag{S16}$$

Eq S15 and S16 shows how to use the CF provided in the SI.xlsx file and in the SI.txt file to calculate the manufacturing facility and the damage in the supply chain.

Table C.1Creation of the Q matrix, an example

Starting with a classification (NAICS) with 5 sectors for which we know the blue-collars worked hours (BCWH):

Sector	BCWH, h_i(h)
NAICS_1	1
NAICS_2	2
NAICS_3	3
NAICS_4	4

We also have an Input-Output classification with only 3 commodities and 3 sectors for which we know the total production:

Sector	Total sector output, gi ($)
IO_c1	10
IO_c2	10
IO_c3	30

Commodity	Total commodity production, q_i ($)

IO_s1	10
IO_s2	20
IO_s3	20

The corresponding make matrix is:

V ($)		Commodities		
		IO_c1	IO_c2	IO_c3
Sectors	IO_s1	5	5	0
	IO_s2	5	5	0
	IO_s3	0	10	20

The mapping between the two classifications is provided by government agencies:

conv_{ij}		IO sectors		
		IO_1	IO_2	IO_3
NAICS sectors	NAICS_1	1	0	0
	NAICS_2	1	1	1
	NAICS_3	0	1	1
	NAICS_4	0	1	1

<u>Step 1:</u>

$$\boldsymbol{CONV_{norm}}$$

We start by calculating the normalized conversion matrix $\boldsymbol{CONV_{norm}}$:

$conv_{norm_{ij}} = \frac{conv_{ij} \times g_j}{\sum_{k=1}^{3}(conv_{ik} \times g_k)}$		IO sectors		
		IO_1	IO_2	IO_3
NAICS sectors	NAICS_1	1	0	0
	NAICS_2	0.2	0.2	0.6
	NAICS_3	0	0.25	0.75
	NAICS_4	0	0.25	0.75

In this matrix, the sum on every row is 1.

Step 2:

$$\widehat{BCWH} \times \boldsymbol{CONV_{norm}}$$

We then multiply every row by the total number of hours worked in the corresponding NAICS sector:

$h_i \times \frac{conv_{ij} \times p_j}{\sum_{k=1}^{3}(conv_{ik} \times p_k)}$		IO sectors		
		IO_1	IO_2	IO_3
NAICS sectors	NAICS_1	1	0	0
	NAICS_2	0.4	0.4	1.2
	NAICS_3	0	0.75	2.25
	NAICS_4	0	1	3

On this matrix, the sum on any row corresponds to the total number of BCWH worked in the corresponding NAICS sector for the whole modelled system.

Step 3:

$$\widehat{BCWH} \times \boldsymbol{CONV_{norm}} \times \widehat{g^{-1}}$$

Each column is then divided by the total production of the corresponding IO sector:

		IO sectors		
		IO_1	IO_2	IO_3
NAICS sectors	NAICS_1	0.1	0	0
	NAICS_2	0.04	0.04	0.04
	NAICS_3	0	0.075	0.075
	NAICS_4	0	0.1	0.1

<u>Step 4:</u>

$$\widehat{BCWH} \times \boldsymbol{CONV_{norm}} \times \widehat{g^{-1}} \times \boldsymbol{V}$$

We multiply the previous matrix by the make matrix (note that we now have commodities in the columns):

		IO commodities		
		IO_1	IO_2	IO_3
NAICS sectors	NAICS_1	0.5	0.5	0
	NAICS_2	0.2	0.8	0.8
	NAICS_3	0	1.125	0.15
	NAICS_4	0	1.5	2

Step 5:

$$\widehat{BCWH} \times \boldsymbol{CONV_{norm}} \times \widehat{g^{-1}} \times \boldsymbol{V} \times \widehat{q^{-1}} = \boldsymbol{B}$$

Now each column is divided by the total commodity production value:

B		IO commodities		
		IO_1	IO_2	IO_3
NAICS sectors	NAICS_1	0.05	0.05	0
	NAICS_2	0.02	0.08	0.04
	NAICS_3	0	0.1125	0.075
	NAICS_4	0	0.15	0.1

We then obtain the **B** matrix.

Table C.2 : Aggregated information for the reproduction of the illustrative case study

- Detail of purchase per functional unit from suppliers at the commodity level

IO Commodities		Value of purchase ($/FU)
313310	Textile and fabric finishing mills	3,84E+01
314990	All other textile product mills	1,14E-01
321219	Reconstituted wood product manufacturing	2,63E+01
322210	Paperboard container manufacturing	1,83E+01
325190	Other basic organic chemical manufacturing	1,63E+01
325211	Plastics material and resin manufacturing	3,27E+01
325510	Paint and coating manufacturing	4,89E-02
326150	Urethane and other foam product (except polystyrene) manufacturing	3,38E+00
331200	Steel product manufacturing from purchased steel	2,70E+00
332720	Turned product and screw, nut, and bolt manufacturing	5,62E-01
483000	Water transportation	1,35E-01
484000	Truck transportation	1,43E+01
32121A	Veneer and plywood manufacturing	4,88E+00
3259A0	All other chemical product and preparation manufacturing	3,01E+00
32619A	Other plastics product manufacturing	6,01E+00

Table C.2 Aggregated information for the reproduction of the illustrative case study (cont.and end)

- Other aggregated data:

Impacts from exposure to organic chemicals at the manufacturing facility	3.15E-06 DALY/FU
Impacts due to exposure to organic chemicals of the user during the use phase	4.06E-07 DALY/FU

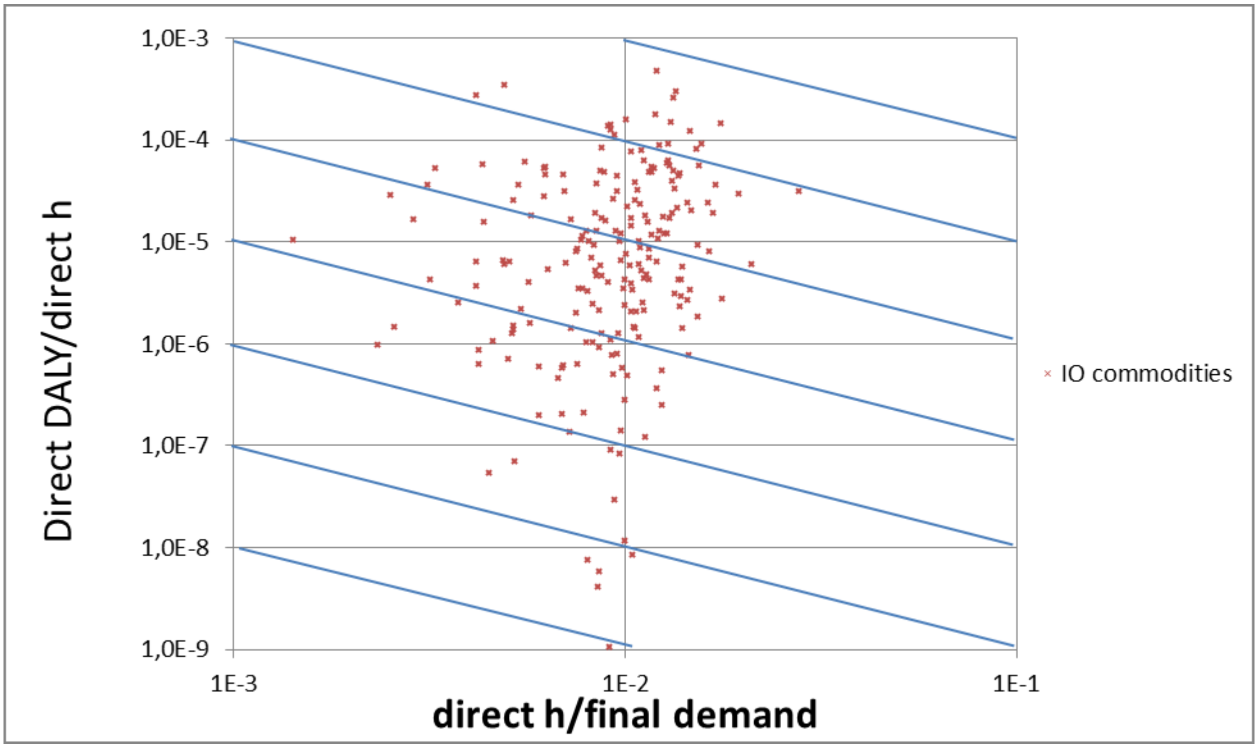


Figure C.2: Direct hour based potential impact intensity (DALY/h) function of direct dollar based labour intensity $

Blue diagonals represent the iso-impact-per-$. Two dots on the same diagonal have the same impact intensity per $ (DALY/$).

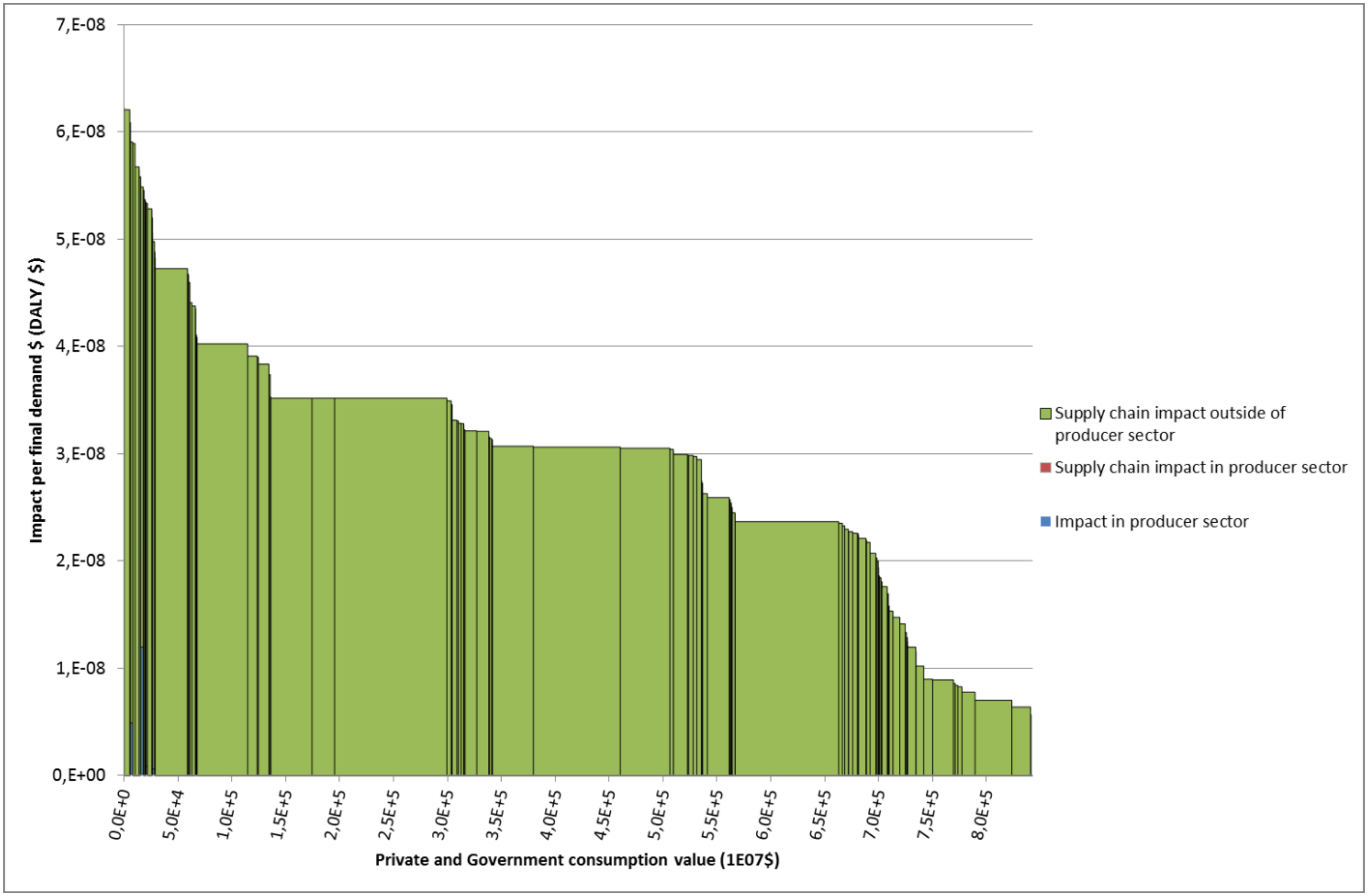


Figure C.3: Overall Occupational Human Health Impact for the 151 non-industrial economic sectors of the U.S. economy with the highest impact intensity. Histograms represent potential impact on human health from occupational exposure to organic chemicals per IO sector as a combination of Impact Intensity, DALY/$ (y-axis) and number of final demand $ for each sector (x-axis).

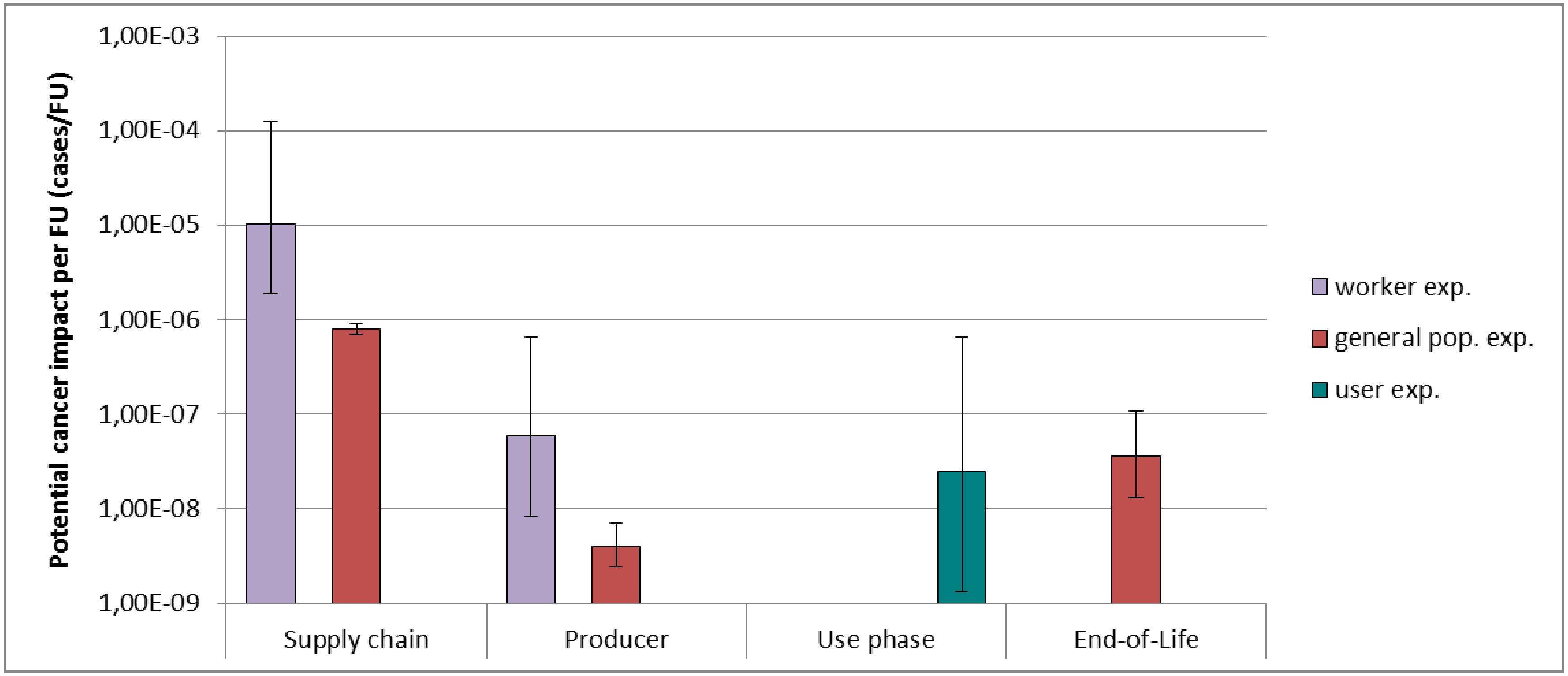


Figure C.4: Contribution of the different phases to the potential cancer impact on Human Health

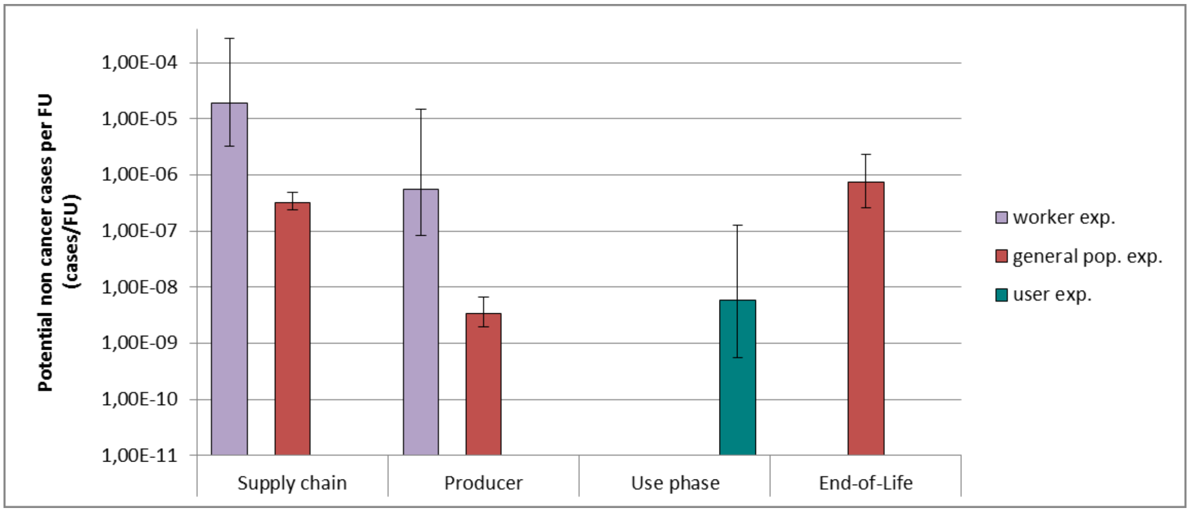


Figure C.5: Contribution of the different phases to the potential non-cancer impact on Human Health

Table C.3 : Detail on proxy available for missing data

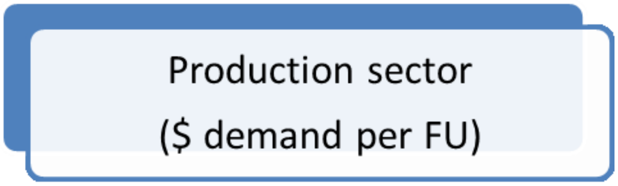
	Value of production	Demand for each supplier	BCWH (h/FU)	Occupational concentration
Proxy data	(Only at producer level) Estimation of value At the tier-n level, this data correspond to the demand for each supplier at the tier-(n-1) level	Calculated: $\boldsymbol{A} \times \vec{Y}$ With **A** being the direct requirement matrix from the IO model and $\vec{Y}$ the vector of demand of commodities per functional unit at the considered level	Calculated: $\boldsymbol{B} \times \vec{Y}$ $\boldsymbol{B}$ being the matrix that provides the direct BCWH worked in each NAICS sector per $ of IO commodity.	Generic concentration (Kijko, et al. 2015) and corresponding direct impact characterisation factors (CF).

When using the developed approach, the practitioner may face a lack of data. This table shows, for each needed data, the method to obtain a proxy data for a given supplier (at a given level in the supply chain) to calculate the full supply chain occupational impacts. For more detail on how to use this data, see figure C.6.

SI-3: PROCEDURE TO APPLY THE METHOD

We will apply the method for a very simple FU: the production of a 1$ painted wooden planck.

1. Simplest case:



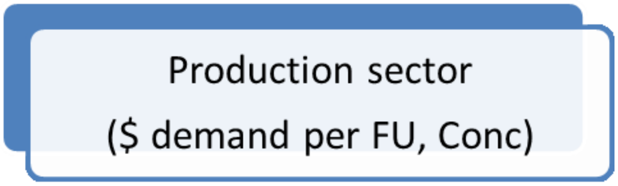
We just know the demand per FU, with corresponding IO commodity (the price of a painted wood planck for exemple).

The total damage is:

$$Total\ damage = \overrightarrow{CF2_{ec}} \times \vec{Y}$$

With all $CF2_{ec}$ provided in the SI.txt file in supporting information or in the SI.xlsx file for the $CF2_{ec}$aggregated by IO commodity.

2. Concentration at manufacturing facility:



Now we have the the demand per FU, with corresponding IO commodities (the price of a painted wood planck for exemple) along with measurements of concentrations.

The total damage is:

$$Total\ damage = Damage\ at\ manufacturing\ facility + Damage\ in\ supply\ chain$$

And: $Damage\ in\ supply\ chain_{ec} = \overrightarrow{CF2_{ec}} \times \vec{Y} - \overrightarrow{CF2\_manufact_{ec}} \times \vec{Y}$

We know $\vec{Y}$, $\overrightarrow{CF2_{ec}}$ and $\overrightarrow{CF2\_manufact_{ec}}$ so $Damage\ in\ supply\ chain_{ec}$ is known.

And:

$Damage\ at\ manufacturing\ facility = \sum_c \vec{C} \times \vec{h} \times BR \times EF_c \times SF$ (see Kijko *et al.* 2015(Kijko et al., 2015)).

The Effect Factors (EF) come from the USEtox model (go to http://www.usetox.org/ to download the model and data).

The Severity Factors (SF) and corresponding GSD2 are the following:

effect	severity Daly/case	GSD2
cancer	11,5	2,7
non-cancer	2,7	13

See Huikbregts et al. 2005(Huijbregts et al., 2005)

The Breathing Rate can be chosen from different sources such as the EPA Exposure Factors Handbook (see https://cfpub.epa.gov/ncea/risk/recordisplay.cfm?deid=236252).

$\overrightarrow{h'}$ is the vector of BCWH worked in each IO sector. It can be obtained by multiplying the $\vec{P}$ vector by the vector of BCWH by $ provided in supporting info (see line 3 of the “B matrix” sheet in SI.xlsx file.

3. supplier demand per FU

Production sector

($ demand per FU, supplier demand per FU)

In this case we know the demand of each IO commodity needed to produce our FU, but we also know the supplier demand per FU (the price of wood and of paint from suppliers for exemple).

The total damage now is:

$$Total\ damage = Damage\ at\ manufacturing\ facility + Damage\ in\ supply\ chain$$

And: $Damage\ in\ supply\ chain_{ec} = \overrightarrow{CF2_{ec}} \times \vec{Y} - \overrightarrow{CF2\_manufact_{ec}} \times \vec{Y}$

We know $\vec{P}$, $\overrightarrow{CF2_{ec}}$ and $\overrightarrow{CF2\_manufact_{ec}}$ so $Damage\ in\ supply\ chain_{ec}$ is known.

And this time

$$Damage\ at\ manufacturing\ facility = \sum_{c} \vec{C} \times \vec{h} \times BR \times EF_c \times SF = \overrightarrow{CF_{Kijko\ et\ al.2015}} \times \vec{h}$$

The CF can be directly extracted from Kijko *et al*. 2015(Kijko et al., 2015). But this time we need to calculate the number of hours worked in each NAICS sector (as the CF are specific to NAICS sectors).

Using the equation $\vec{h} = B \times \vec{P}$ the equation becomes:

$$Damage\ at\ manufacturing\ facility = \overrightarrow{CF_{Kijko\ et\ al.2015}} \times \boldsymbol{B} \times \vec{Y}$$

4. **Concentration, hours and supplier demand at manufacturing facility:**

Production sector

($ demand per FU, Conc, BCWH, supplier demand per FU)

We now have all access to the producer data.

The total damage still is:

$$Total\ damage = Damage\ at\ manufacturing\ facility + Damage\ in\ supply\ chain$$

But this time $Damage\ at\ manufacturing\ facility$ can be calculated as in the previous exemple without the need to calculate the BCWH.

$$Damage\ at\ manufacturing\ facility = \sum_{c} \vec{C} \times \overrightarrow{BCWH} \times BR \times EF_c \times SF$$

Also the $Damage\ in\ supply\ chain$ can be calculated using the real supplier demand per FU instead of using a generic value:

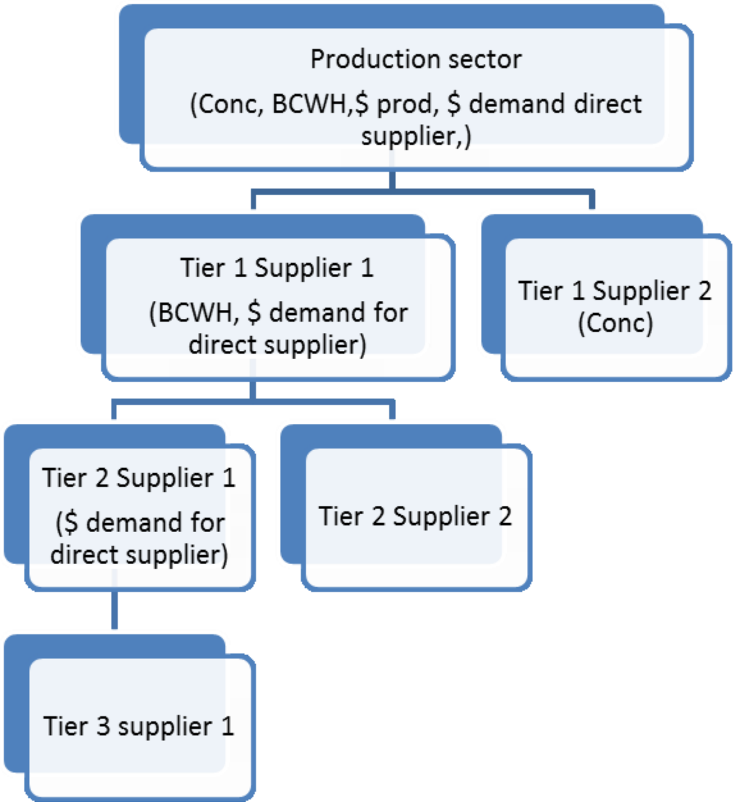
$$Damage\ in\ supply\ chain = \overrightarrow{CF2_{ec}} \times \overrightarrow{\text{supplier demand per FU}}$$

5. Other cases

If more data is accessible, then consider calculating the $Damage\ at\ manufacturing\ facility$ at each level of the supply chain and then move on to the next level, using the points 2 to 4. If you cannot complete a level completely, it is recommended to use the point 1 to calculate the $Total\ damage$ of this level.

Note that the $\vec{Y}$ vector of the first supplier level for a given commodity s is obtained by calculating

$\overrightarrow{Y'_s} = \boldsymbol{A} \times \overrightarrow{Y_s}$, the second level will be $\overrightarrow{Y''_s} = \boldsymbol{A} \times \overrightarrow{Y'_s}$



Here $Total\ damage =$

$Damage\ at\ manufacturing\ facility(Production\ sector)$ Using point 4

$+$

$Damage\ at\ manufacturing\ facility(Tier\ 1\ Supplier\ 1)$ Using point 3

$+$

$Damage\ at\ manufacturing\ facility(Tier\ 1\ Supplier\ 2)$ Using point 2

$+$

$Damage\ in\ supply\ chain(Tier\ 1\ Supplier\ 1)$ Using point 1 as we do not have all data for the Tier 2 Supplier 1

$+$

$Damage\ in\ supply\ chain(Tier\ 1\ Supplier\ 2)$ Using point 1

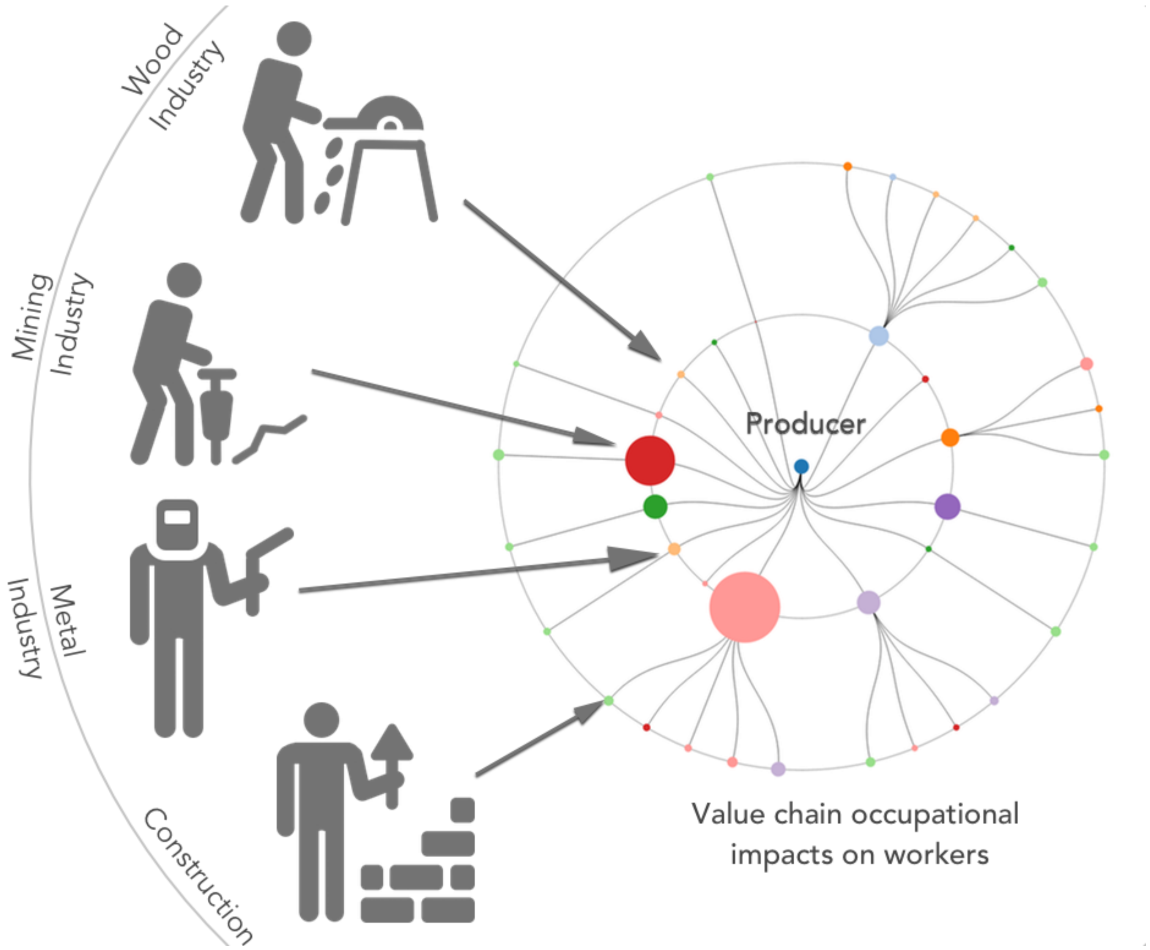


Figure C.6: TOC Art