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BUILDING COMPONENTS AND BUILDINGS

Integrating exposure to chemicals in building materials during use stage

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Abstract

Purpose There do not currently exist scientifically defensible ways to consistently characterize the human exposures (via various pathways) to near-field chemical emissions and associated health impacts during the use stage of building materials. The present paper thus intends to provide a roadmap which summarizes the current status and guides future development for integrating into LCA the chemical exposures and health impacts on various users of building materials, with a focus on building occupants.

Methods We first review potential human health impacts associated with the substances in building materials and the methods used to mitigate these impacts, also identifying several of the most important online data resources. A brief overview of the necessary steps for characterizing use stage chemical exposures and health impacts for building materials is then provided. Finally, we propose a systematic approach to integrate the use stage exposures and health impacts into building material LCA and describe its components, and then present a case study illustrating the application of the proposed approach to two representative chemicals: formaldehyde and methylene diphenyl diisocyanate (MDI) in particleboard products.

Results and discussion Our proposed approach builds on the coupled near-field and far-field framework proposed by Fantke et al. (Environ Int 94:508–518, 2016), which is based on the product intake fraction (PiF) metric proposed by Jolliet et al. (Environ Sci Technol 49:8924–8931, 2015), The proposed approach consists of three major components: characterization of product usage and chemical content, human exposures, and toxicity, for which available methods and data sources are reviewed and research gaps are identified. The case study illustrates the difference in dominant exposure pathways between formaldehyde and MDI and also highlights the impact of timing and use duration (e.g., the initial 50 days of the use stage vs. the remaining 15 years) on the exposures and health impacts for the building occupants.

Conclusions The proposed approach thus provides the methodological basis for integrating into LCA the human health impacts associated with chemical exposures during the use stage of building materials. Data and modeling gaps which currently prohibit the application of the proposed systematic approach are discussed, including the need for chemical composition data, exposure models, and toxicity data. Research areas that are not currently focused on are also discussed, such as worker exposures and complex materials. Finally, future directions for integrating the use stage impacts of building materials into decision making in a tiered approach are discussed.

Keywords Building materials · Exposure · Human health impact · LCA · Near field · Semi-volatile organic compound (SVOC) · Use stage · Volatile organic compound (VOC)

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1 Introduction

By the late 1960s, enclosed glass and steel buildings was popularized as the standard design for buildings in cities and rapidly expanding suburbs. These buildings required massive heating, ventilating, and air conditioning (HVAC) systems that consumed huge amounts of energy for heating and cooling (Cassidy et al. 2003). It was the Organization of Petroleum Exporting Countries (OPEC) oil embargo of 1973 and the ensuing energy crisis that prompted the construction industry and the government to search for ways to reduce the heavy dependence of buildings on fossil fuels through practical measures (e.g., environmentally beneficial siting) and technological solutions (e.g., photovoltaics) (Cassidy et al. 2003). Residential dwellings of this era had little insulation in the exterior walls or attics, and the rise in energy prices had a substantial impact on the residents. Exploiting the advances in energy conservation and renewable energy systems, residential buildings were retrofitted with additional insulation and energy-efficient appliances and heating/cooling systems and were sealed to prevent drafts and air leaks. By the early 1980s, efficiency standards were adopted by several states (Kibert and Kibert 2008), particularly addressing air infiltration rates for newly constructed commercial buildings.

Accompanying the increased tightness of buildings for energy efficiency were increasing concerns about the impact of indoor environmental quality (IEQ) on health. These concerns included exposures to toxic substances, such as friable asbestos in insulation, chemicals like PCBs in caulk and other building materials, radon from surrounding gravel, and lead in paint. Indeed, energy improvements could exacerbate these health concerns, such as releasing asbestos into the indoor environment when existing insulation and HVAC systems were disturbed. The phenomenon of "sick building syndrome" emerged in the early 1980s as the prevalence of complaints of building-related health problems increased (Spengler and Chen 2000). Spengler and Chen (2000) argue that in addition to sealing and reduced ventilation, it was changes in construction from heavy site-built construction to lightweight-premanufactured systems that produced indoor environmental quality issues. More modern materials not only are less forgiving of variations in temperature and humidity but are also less permeable to gaseous compounds which leads to reduced sink area for contaminant absorption (Spengler and Chen 2000). More modern materials, particularly increasingly used synthetic materials for building (e.g., composite wood, PVC) and furnishing (e.g., nylon carpets, polyurethane foams), also have intensified the generation of contaminants due to outgassing and other releases, leading to increased IEQ issues (Weschler 2009). Concerns over IEQ were likely heightened by changes in work habits, including a dramatic increase in women's presence in the labor force at the time (Smith et al. 2016). Gradually, as concerns expanded beyond energy efficiency, a more comprehensive concept of green buildings began to emerge, seeking to more holistically consider a wider range of environmental and resource issues, notably IEQ (Huangfu et al. 2017; Mihelcic et al. 2017).

Numerous pathways led to an enhanced focus on IEQ (US EPA 1989). Notably, the understanding of building design and construction advanced substantially in the mid-1980s, including a growing appreciation of the factors that contribute to poor air quality and its effects on human health. Designs featuring natural materials, daylighting, and improved indoor air quality (IAQ) emerged as part of a "green" solution for sick building problems (Kibert and Kibert 2008). An early milestone of green buildings was the *Environmental Resource Guide* published by the American Institute of Architects with funding from the U.S. Environmental Protection Agency (US EPA). According to the US EPA, green buildings are designed to reduce the overall impact of the built environment on human health and the natural environment by: efficiently using energy, water, and other resources; protecting occupant health and improving employee productivity; and reducing waste, pollution, and environmental degradation (US EPA 2016).

The green building movement reached a major milestone in the 1990s with the introduction of green building rating and certification systems. Maintaining indoor environmental quality is a key component of all green building certification systems. One substantial component of IEQ is related to the releases of various chemicals used in buildings into the indoor air or other exposure pathways, which have not been evaluated and managed in a systematic way. Disparate approaches have been used in green building rating and certification systems to maintain or improve IEQ, such as encouraging ingredient disclosure, discouraging/banning the use of building materials which contain certain chemicals that are harmful to human or ecological health, increasing ventilation rates, or measuring the air concentrations of chemicals (Wei et al. 2015). Measuring air concentrations, however, is generally an option rather than a requirement, with measurement methods and data available for only a few of the thousands of chemicals used in building materials, namely volatile organic compounds (VOCs), formaldehyde, ozone, particulate matter, and carbon dioxide (Wei et al. 2015). Thus, more systematic methods are needed to evaluate and mitigate the impacts of substances used in building materials.

Green building rating and certification systems frequently rely on evaluation tools such as life cycle assessment (LCA) to make potential impacts along the full life cycle more transparent and avoid unnecessarily shifting environmental burdens (Wang et al. 2012). Specialized applications have been developed to simplify and accelerate LCA and facilitate its use in the building sector (Zabalza Bribián et al. 2009), such as the Athena Impact Estimator developed by the Athena Sustainable Materials Institute, and the Building for Environmental and Economic Sustainability (BEES) tool from

the National Institute of Standards and Technology (NIST) Engineering Laboratory. Different LCA models are used under the certification systems to assess the environmental impacts of building materials and to assess whole building impacts (Burkholder et al. 2017), particularly integrating whole building LCA with design options using plug-ins for building information modeling software (Jalaei 2015), but paradoxically previous LCA studies of buildings and building materials (Bartlett and Howard 2000; Berge 2009; Chen et al. 2011; Rajendran et al. 2009) do not consider the human exposures and health impacts during the use stage (i.e., occupancy) of buildings. Recent developments (Wenger et al. 2012; Rosenbaum et al. 2015) have been made to incorporate the indoor air-related health impacts into LCA in the USEtox 2.0 model (www.usetox.org). However, methods are still lacking to estimate the chemical emissions indoors, and a clearer interface between life cycle inventory (LCI) and life cycle impact assessment (LCIA) is needed to evaluate the human health impacts during the use stage of buildings and building materials.

The objective of the present paper is thus to provide a roadmap which summarizes the current status and guides the future development of integrating the chemical exposures and during the use stage of building materials into LCA characterization. Exposure to chemicals within a building material can start from the time of manufacturing, which may include processing, transport, retail storage, construction/installation, and use by occupants. Here, we focus on the restricted use stage of a building material, which starts from the time that the building material is ready to be used by building occupants until the disposal of the material. This restricted use stage typically excludes the construction stage when the building/fixture is being constructed or installed, but in the case of a do-it-yourself (DIY) project or renovation of an existing building, the use stage includes the construction/installation. Thus, the exposures during use stage mainly include the building occupants and may also include construction workers/installers who perform renovations on-site. The scope of the present study is to primarily focus on the building occupants, and also to assess the cumulative exposure for all possible users during the entire use stage, while assessment of individual worker exposures is out of scope of the present study.

More specifically, we aim to:

1. Give an overview of the current knowledge on the exposure to chemicals during the use stage of building materials.
2. Briefly describe the process for characterizing chemical exposures and human health impacts for the use stage of building materials and review the current assessment status.
3. Propose a framework to systematically integrate use stage chemical exposures and associated health impacts of building materials into LCA and present an example.
4. Suggest future directions for further development of integrating the use stage chemical exposures and associated health impacts of building materials into LCA characterization.

2 Current knowledge on chemical exposures from building materials

2.1 Human health effects associated with chemicals in building materials

Chemicals used in building materials can cause various adverse health effects for building occupants. Table 1 shows some of the chemicals and substances which are currently or have been historically used in building materials and their associated adverse health effects. Past information is important since building materials often have a very long lifetime and/or are even repurposed in newer structures. The adverse health effects associated with the chemicals that can be used in building materials can range from short-term reversible effects, such as skin irritation and sensitization, to longer-term irreversible effects such as cancer and neurotoxicity (Table 1). Moreover, studies have shown specifically that the chemicals from building materials can cause adverse health effects in humans (Deutschle et al. 2008; Jaakkola et al. 1999; Wieslander et al. 1999). Thus, these evidences demonstrate the urgent need to account for the use stage chemical exposures and human health impacts in the LCA of building materials.

Different methods have been used to regulate the use of toxic chemicals in building materials. For example, lead-based paints have been banned for use in housing in the USA since 1978. Emission standards have been established for certain chemicals in certain building products, such as formaldehyde in composite wood products (U.S. National Archives and Records Administration 2016). However, emission standards do not exist for most of the chemicals used in building materials, and the methods to systematically evaluate emissions and/or indoor concentrations for those chemicals are also lacking. In addition, even for the chemicals that are well regulated such as formaldehyde, the standards only indicate the desired emission rates and air concentrations (such as 0.09 ppm of formaldehyde for particleboard) (U.S. National Archives and Records Administration 2017) with no associations with human exposure pathways or health impacts, making it impossible to analyze the trade-off between emissions during use stage and other environmental health effects which can occur at other stages of the life cycle. This again confirms the need for a more systematic approach to quantifying and evaluating the chemical exposures via various exposure

Table 1 Examples of materials/substances and chemicals of concern used in building materials and the associated potential adverse health effects

Product categories	Materials/substances	Example chemicals of concern	Example adverse effects[a, b]
Adhesives	Acrylic latex, epoxy resins, polyurethane, silicone	Isocyanates, lead, formaldehyde, PCBs (historical)	Skin irritation and sensitization, respiratory effects, cancer, neurological effects, endocrine effects
Ceilings	Gypsum, fiberglass	Formaldehyde, asbestos[c] (historical)	Eye and skin irritation, cancer, lung disease
Composite wood	Particleboard, OSB (oriented strand board), plywood	Isocyanates, formaldehyde	Skin irritation and sensitization, eye irritation, respiratory effects, cancer
Countertops	Laminates, solid surfaces	VOCs such as formaldehyde, phenol	Eye and respiratory irritation, damage to liver, kidney, and central nervous system, cancer
Flooring	Wood, tile, polyvinyl chloride (PVC)	Formaldehyde, asbestos[c] (historical), phthalates, and other plasticizers	Eye and skin irritation, cancer, lung disease, endocrine effects
Sanitary ware	Flame retardants, pigments	PBDEs, titanium dioxide	Endocrine effects, reproductive effects, cancer
Thermal insulation	Fiber, rigid foam, spray foam	Isocyanates, formaldehyde, asbestos[c] (historical), PBDEs	Skin and eye irritation, respiratory effects, cancer, lung disease, endocrine effects, reproductive effects
Tile installation products	Antimicrobials, water repellents	Perfluorinated silanes, alkylsiloxanes	Respiratory effects
Tiles	Ceramic, porcelain	Lead, cadmium	Neurological effects, liver and kidney damage, cancer
Wallboard	Gypsum, plaster, flame retardants	Asbestos[c] (historical), PBDEs	Lung disease, cancer, endocrine effects, reproductive effects
Carpets including pads	Nylon, wool	VOCs such as styrene, ethylbenzene, xylenes, formaldehyde	Respiratory effects, eye and skin irritation, cancer
Lighting	Compact fluorescent lights	Mercury	Neurological effects
Electrical equipment	Switches, thermostats	PCBs (historical), asbestos[c] (historical), mercury	Endocrine effects, lung disease, cancer, neurological effects
Faucets, solder, galvanized pipe	Chrome fixtures, lead and copper solder	Lead (historical)	Neurological effects
HVAC systems and ductwork	Fiberglass, steel, aluminum	Asbestos[c] (historical), particulates	Lung disease, cancer, heart disease
Pressure-treated lumber	Solid wood, laminate	Chromated copper arsenate (CCA)	Skin changes, blood vessel damage, reduced nerve function, cancer

References: Pharos database (https://www.pharosproject.net), EPA Website (https://www.epa.gov), ATSDR Website (https://www.atsdr.cdc.gov), Guo et al. (2017), Klaassen (2013), Little et al. (1994), Woolrich (1982)

[a] This column presents examples of potential health effects associated with the chemicals of concern in the third column, which is not an exhaustive list of health effects for each chemical. Note that these are examples of potential adverse effects associated with all chemicals listed in the third column, and it is not the case that each chemical in the third column is associated with all of the listed adverse effects

[b] The adverse health effects presented in this column are associated with the chemicals of concern (in the third column) themselves. It does not indicate that those chemicals in building materials specifically cause these adverse health effects

[c] Asbestos are mineral fibers rather than pure chemicals

pathways and the associated human health impacts during the use stage of building materials.

2.2 Data resources for building materials

Numerous resources exist to provide information on chemicals in building materials, and many of them are available online. Table 2 lists several of the most important online resources for building materials. A wide range of types of information is covered by these online resources, including lists of chemicals to be avoided in building materials (e.g., ILFI Red List), databases of chemical compositions of building products (e.g., Quartz), transparency labels for chemical ingredients of building products (e.g., Health Product Declaration), product certifications (e.g., GREENGUARD), and comprehensive libraries which contain chemical compositions and contents of building products as well as indicators for the chemicals' environmental impacts and health hazards (e.g., Pharos). Thanks to the rapid growth of online resources, a lot more data on building materials are available nowadays than 5–10 years ago. However, although a large amount of data on building materials is available, these data are in disparate formats and address different aspects of environmental and health issues. For example, some resources provide lists of banned chemicals (e.g., ILFI Red List), while others provide color coding of chemicals' health hazards (e.g., Pharos); some resources focus on the emission rates of chemicals in building materials (e.g., GREENGUARD), while others focus

Table 2 Selected resources on materials guidance for green buildings

Name/URL	Description
EPA's Recommendations of Specifications, Standards, and Ecolabels for Federal Purchasing http://www.epa.gov/greenerproducts	Published by EPA in 2016 after a multi-year, multi-stakeholder effort to help federal purchasers easily identify credible, effective standards and ecolabels. Provides an assessment of any chemical-related criteria in standards and ecolabels and indicates minimum recommendations for indoor air quality standards. Currently covers 21 key purchase categories from cleaning products to electronics to construction materials.
Pharos https://www.pharosproject.net/	Subscription-based library of building products, chemicals and materials, and certifications and standards, combining manufacturer transparency and independent research to provide in-depth health and environmental information
Quartz: //www.quartzproject.org/	An open database of composition, health hazard, and environmental impact data for common building materials and products. Supported by the Healthy Building Network, thinkstep, Google, and Flux
SPOT by UL Prospector: https://spot.ulprospector.com	A sustainability information database developed for architects, designers, specifiers, and consumers to identify products by sustainable attributes, MasterFormat product codes and building rating system credits (e.g., LEED V4 MR).
GREENGUARD Certification Program http://greenguard.org/en/consumers.aspx	Certification program for interior products and materials that have low chemical emissions. Certified products are listed in the UL SPOT Sustainable Product Database.
Cradle to Cradle Banned Chemicals List http://www.c2ccertified.org/	Third-party verification for products assessed for potential human and environmental impacts across 5 key sustainability characteristics: material health, material reuse, renewable energy, water stewardship, and social fairness.
International Living Future Institute (ILFI) Red List https://living-future.org/declare/declare-about/red-list/	A list of over 800 individual chemicals in 23 classes that are prohibited in materials used in construction that seeks to meet the criteria of the Living Building Challenge. According to ILFI, the list is composed of materials that should be phased out of production due to health concerns.
Declare Product Database https://access.living-future.org/declare-products	A product database from the International Living Future Institute for transparent ingredient reporting and compliance with the Living Building Challenge with information on product manufacture (i.e., assembly location, life expectancy, end-of-life options), ingredients (intentionally added and residuals above 100 ppm), and VOC content.
Health Product Declaration http://www.hpd-collaborative.org/	An ingredient transparency label that includes information about intentional ingredients and known residuals, along with associated health information, for products used in the built environment.
HPD Library http://hpd.smithgroupjjr.org/	Searchable database developed by SmithGroupJJR that contains hundreds of Health Product Declarations that can be accessed free of charge to assist in the LEED documenting process.
Building Green http://www2.buildinggreen.com/	A non-market driven resource for environmental effects of products and help finding alternative products with less harmful impacts. A vast repository of information on product guidance, sustainable materials, design strategies, building science, codes, and certifications.
Level by BIFMA https://level.ecomedes.com/	A certification system for environmentally preferable and socially responsible office furniture and furnishings developed by the Business and Institutional Furniture Manufacturers Association (BIFMA). Categories include materials, energy, health, and social impacts.
Healthy Materials Lab at Parsons School of Design https://healthymaterialslab.org/	Resource library to provide designers, architects, homeowners, and developers with information on building materials and health; includes Healthier Affordable Building Products library of certifications and disclosures for commonly used building materials in affordable housing.

on the original chemical composition of building materials (e.g., Quartz, Pharos). Therefore, a systematic approach to take advantage of these data to help evaluate the use stage chemical exposures and health impacts of building materials is needed.

3 Necessary steps for characterizing use stage chemical exposures and human health impacts for building materials

To assess the human health impacts that can be attributed to the use stage exposures to chemicals in building materials, starting from the amount of chemical contained in the building material (stemming from the LCI), one needs to understand the chemical emission, fate, transport, exposure and potential for toxicological effects.

Chemical emissions The exposure assessments for chemicals in building materials rely on the estimation of chemical emissions from building materials during the use stage. Chemical emissions from building materials is generally a dynamic process, that is, the emission rate will change over the entire use stage. For example, a building material's emission rate of a volatile chemical may decrease steadily over time as the amount of chemical remaining in the building material decreases (i.e., the reservoir decreases) (Deng and Kim 2004; Little et al. 1994). The change in emission rate may vary in other ways, such as when emissions of VOCs are damped by sorption of coatings and paint, until the desorption and other release mechanisms accelerate and exceed sorption and other surface phenomena (Uhde et al. 2001). Then, the emission rate may progressively decrease for extended periods before reaching quasi-steady state. The decay rates are often depicted as first-order or second-order, but may also change with time, such as when "wet" coatings, e.g., paint, that contain VOCs are at first themselves a VOC source. However, with time, the coating will become a barrier to VOCs present in the coated substrate, such as formaldehyde in wood products (Li et al. 2006). The dynamics of chemical emissions from building materials depend on the properties of both the chemical and the particular building material, as well as the building characteristics such as ventilation rate. Studies have shown that VOCs and semi-volatile organic compounds (SVOCs) show distinct emission behaviors in building materials (Cox et al. 2002; Liang and Xu 2015), so different emission models are needed for these two groups of chemicals. Details of these models will be described in Sect. 4.

Exposures Assessing and modeling exposures begins after a chemical has been emitted into the indoor or near-field environment from building materials (Fig. 1). After release, chemicals can be transformed into new chemicals by abiotic or biological processes (Lyman 1995). Humans will be exposed to these newly formed compounds, which may be more toxic and/or more readily bioaccumulated than the parent compounds. The released compound and its transformation products move through the environment and reside in various media, depending on the characteristics of the chemicals and the environmental conditions, for which transport and fate models are needed (Fig. 1). Once the chemical reaches the person, human exposures occur, for which exposure models are needed to estimate the intake dose, the amount of chemical that is taken in by the human body (National Research Council 2007, 2012). As indicated in Fig. 1, physiologically based pharmacokinetic (PBPK) models and dose-estimation tools may be needed to enhance a risk assessment, especially where biomarker data are available. However, dose-response used in LCA directly link the intake to effects and do not require these tools. If needed in the future, where LCA and risk assessment tools are harmonized, internal doses could be first assessed using PBPK models, and then combined with internal dose-response relationships, based on high-throughput toxicity data obtained from in vitro bioassays such as ToxCast (Judson et al. 2010).

Toxicological effects For the characterization of toxicological effects and finally human health impacts, several of the more general recommendations of the UNEP/SETAC life Cycle Initiative (McKone et al. 2006) and the recent workshops held in Utrecht (Csiszar et al. 2016) and Brussels (Hauschild et al. 2017) apply to the case of chemicals in building materials. Currently, human health impacts from building materials can be assessed both at mid-point LCIA (like in TRACI) in terms of comparative toxicity units (CTUs) or at end-point LCIA which already accounts for severity of cancer/non-cancer, as recently added in the latest 2.1 version of USEtox (www.usetox.org). The latter method would express the human health impacts from building materials in disability-adjusted life years (DALYs), which will enable to compare these impacts with the human health impacts from outdoor emissions, such as $PM_{2.5}$ (Fantke et al. 2017).

Currently, effect factors are grouped into two endpoints: cancer and non-cancer. Given that the non-cancer category includes a wide range of acute and chronic diseases, there is a need for future studies to explore the possibility of distinguishing effect factors for various non-cancer endpoints which for example may need to different statistical years of life lost. This topic is being addressed currently by the UNEP/SETAC Life Cycle Initiative (www.lifecycleinitiative.org). For building materials, this is especially relevant (a) for vascular diseases, especially for indoor releases of primary or secondary fine particulate matter, (b) for neurotoxicity with the known impacts related, for example, to lead exposure via paint or via releases from lead pipes in the water supply system, and (c) for reproductive and endocrine diseases, with

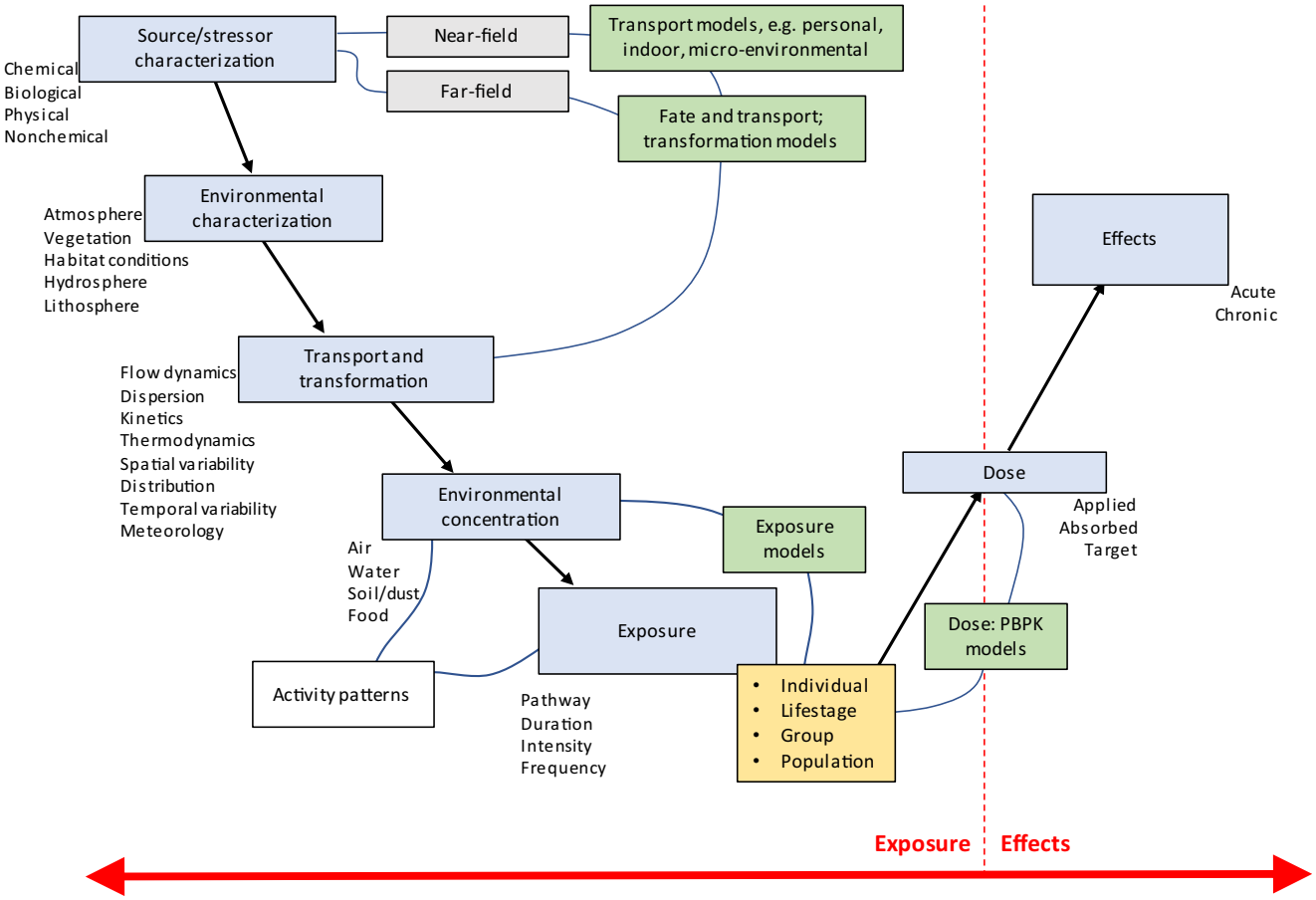

Fig. 1 Source-to-effect continuum. Exposure occurs after a chemical is released into the environment until an adverse effect occurs (e.g., disease and disruption). Steps toward the right of the figure approach the adverse effect. Steps toward the left of the figure approach the source of the chemical (e.g., air pollutant emission), and steps toward the right approach the receptor. Thus, the continuum embodies the "source-to-dose" continuum to the left of the dashed line. PBPK models, physiologically based pharmacokinetic models. Models are shown in green boxes. The yellow box focuses on the receptors of the exposure assessment. The white box represents the necessary psychosocial data to be combined with physical science data. Terms outside of boxes represent the physical, chemical, and biological data needed for each step. Sources: (National Research Council 1991, 2009, 2012; Pleil and Sheldon 2011)

multiple effects of potentially endocrine disrupting chemicals in building materials such as multiple phthalates. Another major challenge to toxicity characterization is the limited present coverage of the tens of thousands of chemicals used in building materials. Based on the Pharos database, of the 756 chemicals identified in building materials, only 184 are in USEtox and only 67 chemicals have human toxicity effect factors (EFs) available, which makes it difficult to assess the human health impacts for many of the chemicals in building materials.

4 Proposed approach to characterize use stage chemical exposures and human health impacts for building materials

As described in the above sections, an approach, which is consistent with other types of LCA impacts and with the intake fraction and dose-response approaches used in traditional LCAs, is needed to assess the human health impacts associated with the use stage of building materials and to integrate these impacts into the LCA of building materials. To address this need, we propose an LCA-compatible approach. The following text will introduce the framework for this approach, describe in detail each component of the framework and present an example to illustrate the characterization process.

4.1 Assessment framework for building materials

The characterization of use stage exposures and health impacts for chemicals in building materials can build on the exposure framework proposed by Fantke et al. (2016) complemented with an improved LCI and information on human toxicity dose-response and eventually disease severity (Fig. 2), which will be discussed in detail below.

For an improved LCI, in addition to the commonly considered environmental emissions occurring during the manufacturing and end-of-life treatment of building materials,

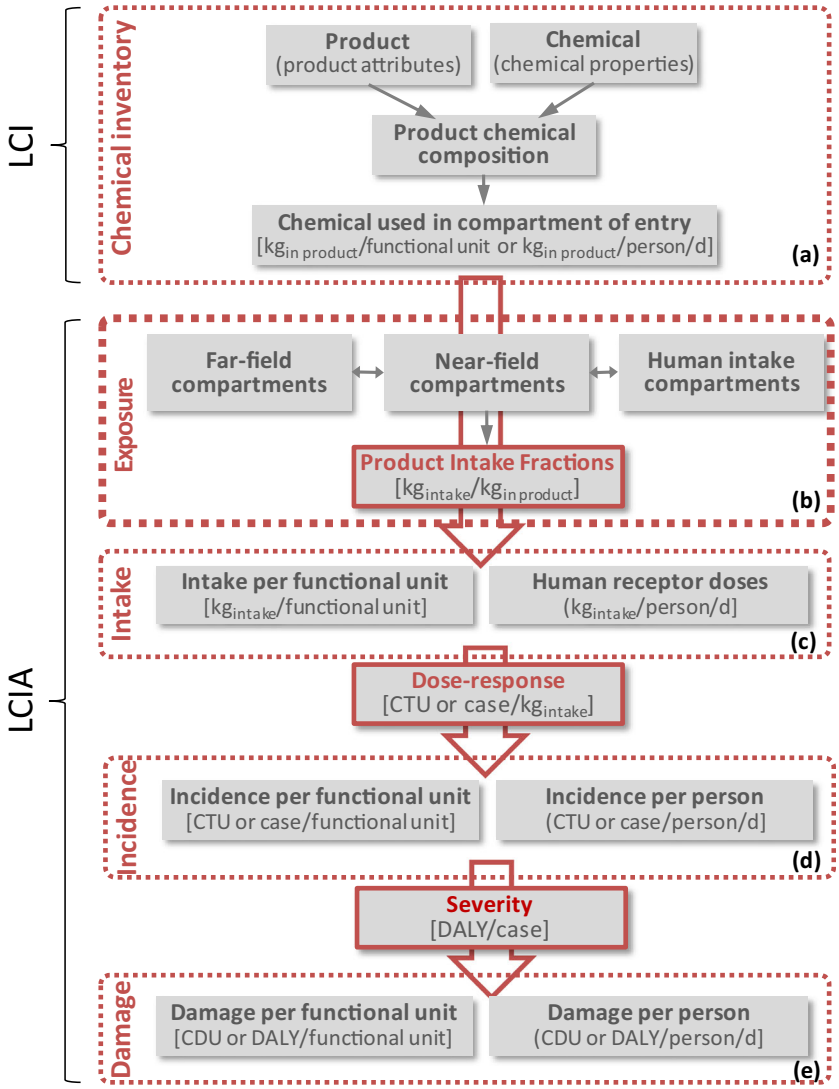

Fig. 2 General assessment framework for chemical exposures and health impacts for building materials during use stage (adapted and extended from Fantke et al. 2016). Compartment of entry, far-field compartments, near-field compartments, human intake compartments, and product intake fraction are defined in the main text. Part (a) shows the construction of LCI; part (b) shows the use of Fantke et al.'s (2016) coupled near-field and far-field framework to determine the product intake fractions; part (c) represents the intake doses which are obtained by combining the outputs from parts (a) and (b); part (d) shows the disease incidences which are obtained by combining part (c) and the dose-response slope; part (e) shows the human health damage which is obtained by combining part (d) and disease severity. CTU, comparative toxicity unit; CDU, comparative damage unit; DALY, disability-adjusted life year

we propose to also combine the amount of material or product used per functional unit (FU) with its actual chemical content to determine the amount of chemicals used per FU as inputs to calculate the building occupant exposures during use stage and to refine the population exposure during disposal stage. Note that our proposed inventory for the use stage is the amount of chemicals initially present in the product, instead of the amount of chemicals emitted to a compartment which is used in traditional LCI, which will be further explained below.

For the exposure quantification part of the LCIA phase, we propose to use Fantke et al.'s (2016) coupled near-field and far-field framework to determine the product intake fraction (PiF) (Jolliet et al. 2015), defined as the fraction of a chemical used in a product application that is cumulatively taken in by the user and by the general population during use and disposal stages. Note that PiF includes exposures during both the use and disposal stages, but the disposal stage is not the focus of the present paper. According to Fantke et al. (2016), near-field compartments refer to any indoor or near-consumer location or environment within the vicinity of the use of a considered product (e.g., indoor air, consumer products and objects themselves, and their surfaces), far-field compartments refer to any location or environment that is distant from the use of a considered product (e.g., ambient air, freshwater, soil, landfill), and human intake compartments refer to any physical location in the interior of humans via which the chemical is first taken in (e.g., respiratory tract, gastrointestinal tract, epidermis); a compartment of entry is the compartment into which or within which a chemical is first applied or used. Briefly, Fantke et al.'s (2016) framework first constructs a matrix **TF** which contains direct transfer fractions between near-field, far-field, and human intake compartments calculated by various models, and then calculates the cumulative transfer fractions by inverting the difference between the identity matrix **I** and **TF**. The resulting cumulative transfer fractions from the compartment of entry to various human intake compartments are thus PiFs by different exposure routes. (Fantke et al. 2016) Multiplying the PiFs by the amount of chemical used per FU

determined in the LCI phase yields the intake per FU as output of the exposure assessment. This framework (Fantke et al. 2016) allows the determination of both a per functional unit approach and a more risk assessment-oriented approach based on individual doses expressed in milligrams per kilogram of body weight per day or in kilograms per person per day. The present paper uses Fantke et al.'s (2016) framework to illustrate and further detail and discuss the specific case of building materials, which was just marginally addressed by Fantke et al. (2016).

Once the intake doses are determined, they can be multiplied by the dose-response slope to calculate the disease incidence which is expressed in cases per FU or cases per person per day. The disease incidence can then be multiplied by the severity factors characterizing disease severity to obtain the final human health impacts, expressed in DALYs. The human health impacts in DALYs can be compared with the human health impacts across different life cycle stages of the building materials.

It should be noted that our proposed systematic approach to assess the use stage impacts is different from the traditional LCA methods which have focused on manufacturing and distribution phases. While traditional LCA methods calculate the inventory as the amount of chemicals emitted to the environment during the considered life cycle stages, our proposed approach uses the amount of chemicals initially present in the product as the inventory output for the use stage. This inventory can be easily harmonized with the traditional LCI as they are both linked to the functional unit of the product. The impact assessment for the use stage thus includes both the chemical releases from the product and the resulting human exposures, which are represented by the PiF values. This applies to not only building materials but also other consumer products. This is because unlike the far-field emissions during manufacturing and distribution phases, the near-field emissions during use stage are dependent on the characteristics of the indoor environment and the users, such as ventilation rate, number of occupants indoors, etc. Moreover, for certain exposure pathways the chemicals in the product are directly transferred to humans without being emitted to indoor media, such as exposure through direct dermal contact. Thus, only the chemical amount present in the product at the beginning of use stage is solely determined by the product itself, so it is used as the inventory, while the near-field emissions and resulting exposures must be modeled simultaneously to obtain the PiFs. The PiF, as an exposure metric, is compatible with the intake fraction metric, which allows for the extension of existing multimedia models such as USEtox 2.0 to also include exposures originating from consumer products (Fantke et al. 2016). PiFs can be further linked to toxicity EFs to yield characterization factors normalized per chemical mass in product instead of chemical mass emitted (Fantke et al. 2016). This way, the proposed approach can be fully compatible with existing LCA methods in estimating exposures and human health impacts based on the functional unit of an assessment.

4.2 Components of the framework

4.2.1 Assessment of product usage and chemical content

Product usage first needs to be determined per FU. This is done by determining the typical area, volume, and weight of product used per FU, accounting for the lifetime of the product. For example, if the FU is 1 m^2 of well-covered flooring for 10 years, the volume per FU of a 3-mm-thick vinyl flooring usable for 20 years will amount to $0.003\ m \times 1\ m^2 \times 10\ years/20\ years = 0.0015\ m^3$ flooring FU^{-1}. Considering a density of $1500\ kg\ m^{-3}$ yields a product amount of $2.25\ kg\ FU^{-1}$.

For chemical content, no peer-reviewed literature has reported non-targeted measurements (i.e., measurements of any possible chemical that could present in the material) of chemical content in building materials. Non-targeted measurements are important since they provide information on all chemicals in a material, which allow for comprehensive assessment of the exposures and health impacts associated with the chemicals in building materials. A few papers provide non-targeted measures of chemical composition of building materials in the form of emissions testing but these are more common for organics than inorganics (An et al. 2010; Jiang et al. 2017). Thus, data on chemical content in building materials can only be obtained from limited sources, as described below.

Fact sheets from the manufacturer are becoming available, such as environmental production declarations (EPDs), which are expected to provide the most accurate data on chemical composition and content of products. However, EPDs are not available for all building materials in the market. In practice, databases are being constructed to systematically record chemical composition and content in building materials based on manufacturer disclosures and independent research, such as the Pharos database developed by the Healthy Building Network (HBN) (www.pharosproject.net).

According to the Pharos database, the mean content of dibutyl phthalate in an engineered flooring product is 0.03% (details are presented in the Electronic supplementary material (ESM) Sect. S1). Multiplying the product usage per FU by the chemical content yields the chemical usage per FU, equal to $0.03\% \times 2.25\ kg\ FU^{-1} = 7.5 \times 10^{-5}\ kg\ FU^{-1}$ in our above example of a vinyl flooring.

In addition to the FU-based approach, it can also be of interest to determine the amount of chemical used per person and per day as an input for calculating individual exposure doses, which will require additional parameters such as the total area and volume of the building material and the number of occupants in the room.

4.2.2 Assessment of human exposures

For building materials, the chemicals usually enter the near-field environment from the interior or the surface of a solid material. During the use stage, the relevant direct transfer fractions from a building material include the chemical fraction released to indoor air via volatilization over product lifetime, as well as the non-released fraction that is transferred to the landfill. Relevant exposure pathways for which exposure models are needed include inhalation of the fraction volatilized to indoor air, gaseous dermal intake from indoor air to skin epidermis, dermal intake via physical contact with the building materials, as well as chemical transfer from building materials to settled dust (via abrasion, direct partitioning, etc.) and subsequent ingestion intake through hand-to-mouth or object-to-mouth activities (Fig. 3). We will briefly review classes of models that are available or needed for each of these exposure pathways.

a. Models for chemical emissions from building materials

For organic chemicals, various models have been developed to calculate the chemical emissions from building materials. Different models need to be applied for VOCs (Deng and Kim 2004; Huang and Haghighat 2002; Huang and Jolliet 2016) or SVOCs (Little et al. 2012; Liu et al. 2013), usually classified as a function of the chemical's boiling point (BP): chemicals with BP less than or equal to 250 °C measured at a standard atmospheric pressure of 101.3 kPa are classified as VOCs, while the others are classified as SVOCs (US EPA 2017b).

For VOCs, the parsimonious model developed by Huang and Jolliet (Huang and Jolliet 2016) is suitable to be used for high-throughput purposes. This model, which takes a form of two exponential terms, describes the diffusion of chemical from inside the building material to the surface of the material, the transfer of chemical from the building material surface to indoor air by convective mass transfer, and the loss of VOCs by ventilation only (Huang and Jolliet 2016).

For SVOCs, a simplified model developed by Little et al. (2012) can be used to estimate the chemical emissions from building materials. This model assumes constant SVOC concentrations in building materials over time and steady-state in indoor air, and it considers the loss of SVOCs by ventilation and sorption to other indoor surfaces which are treated as infinite sinks (Little et al. 2012).

For inorganic substances such as metals, asbestos, and fiberglass, our proposed framework is valid with respect to the calculation steps; however, models are lacking to estimate their emissions from building materials. Generally, inorganic chemicals do not evaporate from the building material, but enter indoor environments through abrasion and aging which are not addressed by current models.

b. Models for human exposures

There are four possible near-field exposure pathways for chemicals in building materials: inhalation intake (of chemicals volatilized to indoor air), dermal gaseous uptake (of chemicals volatilized to indoor air), dermal intake (via physical contact with the building material), and ingestion intake (of chemicals transferred to settled dust via abrasion, direct partitioning, etc.)

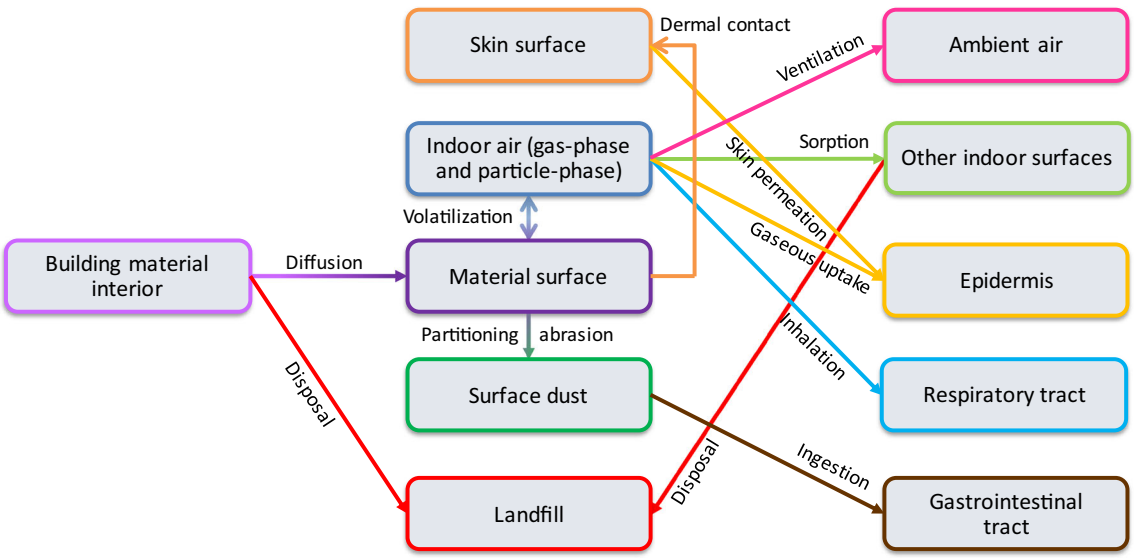

Fig. 3 Transfer and exposure pathways for chemicals in building materials during the use stage. Each box represents a near-field, far-field, or human intake compartment, and each arrow represents a transfer or exposure process

The *inhalation intake* can be calculated by simply multiplying the air concentration by the inhalation rate. Alternatively, in the case the chemical sorption on other indoor surfaces is negligible, the fraction emitted from building material to indoor air can be directly multiplied by an indoor intake fraction (Rosenbaum et al. 2015) to yield the inhalation product intake fraction. Care must however be taken to ensure that the same indoor assumptions (in particular, the ventilation rate) are used in the modeling of the released fraction and the intake fraction.

Dermal exposure comes from two sources: dermal gaseous uptake of chemical in the gas phase of indoor air and dermal contact with the building material. Skin uptake of gaseous chemicals can be estimated assuming that the concentration on skin surface lipids is in equilibrium with the concentration in gas phase. Intake is then calculated by multiplying the concentration in gas phase by a total gaseous-skin permeation coefficient and the exposed skin area (Csiszar et al. 2016; Ernstoff et al. 2016; Weschler and Nazaroff 2012). For dermal contact, currently no models exist to estimate the intake, so we propose that the intake may be calculated by assuming equilibrium between the concentration in the skin-surface lipids and the material surface, analogous to the calculation of dermal gaseous uptake (Csiszar et al. 2016; Ernstoff et al. 2016; Weschler and Nazaroff 2012), and then accounting for the contact area, skin permeability coefficient, and the fraction of time in contact with the building material.

For the *ingestion intake* via *dust*, chemicals in dust can come from two building material transfer pathways: the partitioning between indoor air and surface dust, and the abrasion of building material which directly becomes surface dust. Previous studies have estimated the dust ingestion intake by assuming the chemical concentration in surface dust is in equilibrium with the concentration in indoor air (Bennett and Furtaw 2004; Little et al. 2012). Alternatively, we propose that the dust ingestion intake can be estimated by assuming the concentration in surface dust is in equilibrium with the concentration on building material surface, as determined by a material-dust partition coefficient, analogous to the use of air-water partition coefficient combined with the skin permeation coefficient to calculate dermal gaseous uptake in a previous study (Weschler and Nazaroff 2012), accounting for the dust ingestion rate and the fraction of ingested dust that is from the considered building material.

4.2.3 Assessment of toxicity

Human health EFs for certain chemicals can be obtained from USEtox (www.usetox.org). For chemicals that are not available in USEtox, toxicological effects can be characterized using dose-response information from various sources such as ChemID plus (chem.nlm.nih.gov/chemidplus) and ECHA database for registered substances (echa.europa.eu/information-on-chemicals/registered-substances), combined with severity factors (Huijbregts et al. 2005). These data can be used to determine human health characterization factors, building on earlier recommendations of the UNEP/SETAC life Cycle Initiative (McKone et al. 2006) and on further advancements made in the development of USEtox (Rosenbaum et al. 2011) and in the Human Exposure Modeling (HEM) project (Csiszar et al. 2016) possibly modifying linear dose-response curves to account for the present level of exposure in the considered population.

4.3 Proof-of-concept characterization example

Here, we present a proof-of-concept case study to illustrate the process of applying the approach described in Sects. 4.1 and 4.2 to characterize the use stage chemical exposures and health impact for a building material. The purpose of this case study is to provide an illustrative example for representative chemicals in a specific use scenario, rather than a comprehensive assessment for all chemicals present in building materials. In the case of decision making, all parameters should be refined adapting to real-case scenarios.

In this case study, we assumed that particleboard was used to construct some fixtures in a DIY project in a typical North American house. Thus, the use stage of the particleboard includes the construction and the subsequent use by the house occupants. The human exposures during the use stage for a VOC and an SVOC was characterized. According to the Pharos database, one type of particleboard product contains formaldehyde, a VOC at maximum content of 0.1%, and methylene bisphenyl diisocyanate (MDI), an SVOC at maximum content of 10%. The persons being exposed are 2.44 adults, average number of adult occupants in a North American household (for details see Table S1, Electronic supplementary material (ESM)).

Two fixtures made by the particleboard were compared: (1) a desk considered as a horizontal surface with frequent dermal contact and (2) a kitchen cabinet side panel considered as a vertical surface with no dermal contact. For each application, an FU of 1 m^2 usable for 15 years is considered, which results in 16 kg particleboard FU^{-1} assuming a thickness of 0.02 m and a density of 800 kg m^{-3} based on common particleboard properties (Puuinfo Ltd. 2018). The mass of chemical per FU reflects the difference in chemical content and is 100 times higher for the SVOC MDI than for the VOC formaldehyde.

Although the particleboard used in furniture and cabinets is typically finished with laminate or veneer which would potentially alter the transfer of chemicals from particleboard to the environment, for this illustrative example, we assumed a pure particleboard without any finish to calculate the chemical transfers and no losses before installation is performed in the house. In this respect, the exposure model calculations

presented here represent a proof-of-concept high-end scenario. This issue will be further discussed in Sect. 5.

As described in Sects. 4.1 and 4.2, the direct transfer fractions between various compartments were calculated using the models described in Sect. 4.2.2 and were then used to construct the matrix **TF**, and the PiFs were obtained by inverting the difference between the identity matrix **I** and **TF**. The detailed equations and input data for this case study are presented in the ESM Sect. S2.

It should be noted that the models are able to calculate the PiFs for any time interval in the 15-year use stage. For illustration purposes of this case study, we have focused on two extreme time intervals: the very beginning (0–50 days) and the remaining (50 days–15 years). The time zero refers to the time the particleboard is brought into the house. Thus, the very beginning of the use stage (0–50 days) mainly include the construction of the cabinets and desk, while for the remaining of the use stage (50 days–15 years), it would be primarily the use of these fixtures. Since this is a DIY project, the persons exposed are always the house occupants. By contrasting the results between these two intervals, we can roughly compare the exposures and health impacts during DIY construction/renovation to those during everyday use.

The results of the case study are presented in Table 3. During a 15-year use stage (sum of 0–50 days and 50 days–15 years), the VOC formaldehyde in the particleboard will have 100% released to indoor air, most of which (91%) will be released during the first 50 days. For the kitchen cabinet and desk, the inhalation PiF and dermal gaseous PiF are the same for a given time interval, while the desk has additional dermal contact PiF and dust ingestion PiF due to the considerable dermal contact with the desk. For both time intervals, inhalation is the dominant exposure pathway during the use stage for formaldehyde in particleboards, regardless of dermal contact potential or orientation.

On the other hand, the SVOC MDI in the particleboard will have only 3% released to indoor air during the first 50 days (Table 3). For the entire 15-year use stage, the exact amount of fraction released to air for MDI is uncertain and overestimated to be greater than 1, since Little et al.'s model assumes constant SVOC concentration in building material over time (Little et al. 2012), which is only valid for MDI for a short period of time instead of 15 years. However, Little et al.'s model also shows that the majority of MDI released to air will be adsorbed into other indoor surfaces and will not be available for human exposures, so the net release to air estimated by this model is likely to be more reliable and is thus used to calculate the PiFs. This issue highlights the need to develop an improved model to estimate the emission of SVOCs from building materials, which is valid for SVOCs with various physiochemical properties and over different time periods.

In terms of the exposure pathways for the SVOC MDI, inhalation is no longer a dominant pathway (Table 3). For the kitchen cabinet, the dermal gaseous uptake is the dominant pathway for MDI, while for the desk both dermal gaseous uptake and dermal contact are dominant, and the contribution of dust ingestion exposure also starts to be significant. The dermal contact and dust ingestion pathways significantly increase the total intake dose for MDI in the office desk compared with kitchen cabinet, highlighting the importance of dermal contact potential and material orientation for exposure to SVOCs. The total intake doses for MDI for both time intervals are substantially higher than those for formaldehyde, mainly due to the much higher content of MDI in particleboard.

As described above, results in Table 3 compare the exposures between the very beginning (0–50 days) and the remaining (50 days–15 years) of the use stage, which can roughly represent a comparison between DIY construction/renovation and everyday use. For the VOC formaldehyde, the PiFs and daily doses for 0–50 days are much higher than those for 50 days–15 years, because most of the formaldehyde in the particleboard is released during the initial days of the use stage. In contrast, for the SVOC MDI, the PiFs are significantly increased for a longer time interval (i.e., 50 days–15 years), but the daily intake doses remain fairly constant for different time intervals. The reason is that the MDI is released from the particleboard very slowly, and the MDI released to indoor air will be adsorbed by other indoor surfaces and then back-released to indoor air, resulting in nearly constant emission over the entire 15-year use stage. Therefore, these results suggest that during the construction/renovation, building occupants would get much higher exposures to VOCs but similar exposures to SVOCs in building materials compared with everyday use. It also highlights the importance of use duration in assessing exposures during use stage, especially in assessing daily intake doses for VOCs and assessing cumulative exposures for SVOCs.

The human health impacts from use stage exposures to the considered products can be obtained by combining the daily intake or cumulative intake and the EFs expressing the impact per kilogram intake. For formaldehyde, cancer and non-cancer EFs for inhalation and ingestion pathways are available from USEtox (www.usetox.org). For MDI, no dose-response factors are available in USEtox. MDI is classified as Group 3—not classifiable as to its carcinogenicity to humans—by the International Agency for Research on Cancer (IARC). However, MDI acts as an asthmagen. Once sensitized, re-exposure to even low concentrations of MDI may trigger severe asthma attacks. In addition, exposure to MDI can cause other adverse respiratory effects including inflammation and irritation, as well as dermatotoxic effects such as allergic contact dermatitis. (Guo et al. 2017) This demonstrates the need for the development of dose-response factors for MDI and many other chemicals in building materials.

Table 3 Use stage exposures of one adult to formaldehyde and MDI in a particleboard desk and kitchen cabinet, as well as human health impacts

Metric for FU = 1 m^2	Formaldehyde 0–50 days	Formaldehyde 50 days–15 years	MDI 0–50 days	MDI 50 days–15 years
Board mass (kg FU^{-1}) = (kg m^{-2})[a]	16	16	16	16
Chemical content (−)[b]	0.10%	0.10%	10%	10%
Chemical mass (kg FU^{-1}) = (kg m^{-2})[c]	0.016	0.016	1.6	1.6
Number of exposed persons[d]	2.44	2.44	2.44	2.44
Fraction released to air (−)	9.06E−01	9.40E−02	2.97E−02	–[g]
PiF_inhalation (−)	4.33E−03	4.47E−04	9.45E−06	1.34E−03
PiF_gaseous dermal (−)	6.83E−07	1.05E−06	1.22E−04	1.15E−02
PiF_dermal contact (−)[e]	2.10E−04	2.04E−05	4.65E−04	5.05E−02
PiF_ingestion (−)[e]	1.91E−13	1.97E−14	5.38E−06	5.84E−04
Cumulative intake_inhalation (kg FU^{-1}) = (kg m^{-2})	6.93E−05	7.15E−06	1.51E−05	2.14E−03
Cumulative intake_gaseous dermal (kg m^{-2})	1.09E−08	1.68E−08	1.95E−04	1.84E−02
Cumulative intake_dermal contact (kg m^{-2})[e]	3.35E−06	3.26E−07	7.44E−04	8.08E−02
Cumulative intake_ingestion (kg m^{-2})[e]	3.05E−15	3.15E−16	8.61E−06	9.34E−04
Daily dose_inhalation (mg kg^{-1} body day^{-1})	7.10E−03	6.75E−06	1.55E−03	2.02E−03
Daily dose_gaseous dermal (mg kg^{-1} body day^{-1})	1.12E−06	1.58E−08	2.00E−02	1.74E−02
Daily dose_dermal contact (mg kg^{-1} body day^{-1})[e]	3.44E−04	3.08E−07	7.63E−02	7.63E−02
Daily dose_ingestion (mg kg^{-1} body day^{-1})[e]	3.12E−13	2.97E−16	8.82E−04	8.82E−04
Daily dose_total (mg kg^{-1} body day^{-1})[f]	7.44E−03	7.07E−06	9.87E−02	9.65E−02

[a] Assumed a thickness of 0.02 m and a density of 800 kg/m^3 based on common particleboard properties (Puuinfo Ltd. 2018)

[b] Reference: Pharos database (https://www.pharosproject.net)

[c] Calculated by multiplying board mass and chemical content

[d] Reference: see SI Sect. S2.2

[e] Desk only, no contact assumed for kitchen cabinet side panel

[f] Total daily dose for desk

[g] The exact amount of fraction released from 50 days to 15 years for MDI is uncertain and overestimated due to Little et al.'s model assumption of constant concentration in building material which is not valid for MDI over 15 years. However, the net release to indoor air estimated by Little et al.'s model is likely to be more reliable and is used to calculate the PiFs below (see main text for more explanations)

5 Future research needs

The proposed approach described in Section 4 provides the methodological basis for integrating use stage chemical exposures for building materials into LCA. However, to make this approach easily applicable to LCA or building certification systems for the thousands of chemicals in building materials, significant advancements are needed in three aspects: chemical composition of building materials, exposure estimates, and toxicity data.

The assessment of human health impacts in LCIA begins with the quantification of the chemical amount used in building materials, so knowledge on the chemical composition and content of building materials is crucial. A few databases link the chemical compositions with specific building materials (Table 2); the Pharos database is one of the most useful. However, even Pharos cannot be considered comprehensive. For certain building products, only a general composition is available in Pharos, which does not necessarily reflect the true chemical composition of the specific products. Also, for some building products, the contents of certain chemicals span an unreasonably wide range in Pharos, such as from 0 to 100%, making these data less reliable. Therefore, additional access to building material compositions is needed. Increasing the transparency of the supply chain by providing information on the ingredients of as many building materials and products as possible could be a way to increase our knowledge on the chemical composition of building materials. Several efforts have been undertaken to open the supply chain over the past decade or so that support and encourage transparency of product design. The concept of chemical footprinting, a metric specifically addressing the use and disclosure of chemicals of high concern rather than a comprehensive assessment of all relevant impacts and trade-offs (Ridoutt et al. 2015), has been advanced as a means of improving the transparency of substances in the supply chain by encouraging industry to adopt a declaration of adherence to reducing hazard through safer product adoptions (http://www.chemicalfootprint.org). To further encourage the efforts to reveal the chemical content of materials and products at the manufacture stage,

other methods can be employed, including business incentives, responses to public demand, or through regulatory requirements. The advantage of obtaining chemical composition data through a priori declaration instead of after-sale testing is that it provides industrial and citizen purchasers timely, useful information upon which to make informed health decisions. This also offers innovation opportunities for product designers and green chemists to develop safe, sustainable chemicals and products.

The second research need is to obtain systematic, large-scale estimates for the multi-pathway exposures to chemicals in building materials during use stage, that is, the PiF values used in our proposed framework. The PiF values represent the fraction of a chemical used in a building material that is cumulatively taken in by different users during the use stage and by the general population during disposal. As demonstrated by modeling studies (Deng and Kim 2004; Huang and Haghighat 2002; Huang and Jolliet 2016), PiFs are only determined by the properties of the chemical and the building material (e.g., material area, thickness, chemical's diffusion coefficient in the material), the characteristics of the building and human occupants (e.g., room volume, ventilation rate, inhalation rate), and the exposure duration, but are independent of the initial chemical concentration in the building material. Thus, given the standard characteristics of residential buildings and human occupants, PiFs can be calculated for any given chemical-building material combination for the building material's lifetime. Since multi-pathway PiFs are calculated by different underlying models which may range from simple multiplication to complex numerical simulation, a large set of PiF values for the thousands of chemical-building material combinations need to be pre-calculated to facilitate the application of the framework for integrating use stage health impacts into building material LCA. Developments in two aspects are needed for this large-scale pre-calculation of PiFs. First, the calculation of multi-pathway PiFs require models for chemical emissions from building materials and the various exposure pathways. Multi-pathway PiFs are important since they need to be combined with different EFs for different exposure routes to calculate the health impacts, as done in our case study and also in USEtox. Currently, models to calculate PiFs for certain emissions and exposure pathways are unavailable or are not well developed, such as the SVOC emissions as mentioned in Sect. 4.3, as well as the dermal contact pathway and the dust ingestion pathway, so further development of chemical emission and near-field exposure models is needed. Second, the large-scale pre-calculation of PiFs require consistent estimates of input parameters for the large amount of chemical-building material combinations, such as the chemical diffusion coefficient in the material and the chemical's material-air partition coefficient. Currently, limited experimental data are available for these coefficients, and correlation methods are only applicable to limited chemical-material combinations. Thus, more comprehensive correlation methods applicable for a wide range of chemical-material combinations need to be developed to estimate the input parameters in a high-throughput manner.

For toxicity data, human health EFs are lacking for most of the many chemicals used in building materials. Two options can be pursued to extend the coverage of toxicity data for chemicals in building chemicals. First, we can take advantage of the large number of in vivo acute toxicity data that have been made available (US EPA 2017a). The second possibility is the use of the large in vitro datasets generated from high-throughput assays such as the Toxcast or Tox21 datasets (Judson et al. 2010). It is important to ensure consistency across chemicals and with previously existing in vivo data, assessing best estimates of dose-responses rather than conservative effects. Another research need to be able to use such in vitro data is to relate external to internal doses using either toxicokinetic data (Shin et al. 2015; Wetmore et al. 2012) or generic PBPK models adaptable to a large number of chemicals (Gong et al. 2016). In addition, new methods for non-cancer dose-response are being developed within the LCIA guidance project of the Life Cycle Initiative (Fantke et al. 2018). Moreover, current EFs are only for the inhalation and ingestion routes, but dermal exposure is also an important route for chemicals in building materials, so future development of dermal EFs is also needed.

There are several research areas that are currently not addressed by the approach presented here and need further developments. First, worker exposures during the construction stage and disposal of building materials are not fully addressed. The PiF by definition covers the exposures during both the use stage and the disposal stage (Jolliet et al. 2015). However, the exposure models presented in this paper and the case study only focus on the exposures during use stage. In fact, workers doing disposal of building materials might be exposed to higher exposures to certain chemicals, especially for SVOCs, metals and asbestos which are mostly released during renovating/dismantling of old materials (Connors and Duane 2014; Schroeder 2016; Scott and Snyder 2015). Thus, models for estimating occupational exposures during the disposal stage of building materials need to be developed. In addition, as indicated by our definition of the use stage, the construction/installation of buildings/fixtures which involve various workers, is not included in the use stage except for DIY projects. In fact, the approach presented in this study can also be applied to the construction stage, but all parameterizations (e.g., building occupancy, air exchange rate, exposure duration, etc.) should be changed to better represent the working environment and the specific exposure pathways for the workers during construction.

The second research area is estimating chemical emissions and resulting exposures for complex building materials. Building materials such as particleboards, are typically finished

with laminate or veneer, or are covered by a layer of painting or coating. These surface layers may have different physical properties and/or chemical compositions from the material underneath and would potentially alter the transfer of chemicals from the underlying material to the indoor environment. The emission and exposure models described in the present study only assume pure, single-layer building materials. There are models existing to estimate the chemical emissions from multi-layer materials, but they are generally complex and computation intensive (Deng et al. 2010; Kumar and Little 2003; Yan et al. 2009; Yuan et al. 2007; Zhang and Niu 2004), so further developments are needed to simplify these model to make them suitable for large-scale, high-throughput calculations. Moreover, correlation methods also need to be developed to estimate model input parameters for these surface layers.

The third area is to account for the transformation products of chemicals released from building materials. As shown in Fig. 1, chemicals can transform upon release through different processes. The current approach only considers the originally released chemicals, however, the transfer fraction framework could also be used to account for transformation products. If the fraction transformed (kg transformation product kg^{-1} parent compound) is known, this fraction can be considered as a net loss for the parent compound and entered as an emission to a new transfer fraction matrix **TF**.

Filling the knowledge and data gaps for the proposed approach is just the first step toward integrating the use stage chemical exposures and health impacts for building materials into LCA characterization. To better manage and mitigate these exposures and impacts, integration in decision making is necessary for which a tiered approach may be employed. The *first tier* is a qualitative assessment of chemicals of concern and exposure pathways in the design phase of building materials and buildings. The greatest opportunities to reduce health impacts of use stage exposure to chemicals is at the design phase (Basbagill et al. 2013). Making choices at this stage to use components and materials that do not expose humans to known hazardous substances reduces or eliminates potential exposures at the manufacture, use and disposal stages. Lessons learned from previous building material LCAs on chemicals and products that are hazardous to human and ecological health can help formulate general principles for future designs of building materials and buildings. However, this qualitative assessment is mostly based on short-term exposures and effects, and there is only limited knowledge on the potential impacts of many new substances used in building materials; also, in practice this first tier is often impossible because the building product is already in commerce by the time a practitioner is asked to assess its health impacts. Therefore, the *second tier* is needed, which is a quantitative assessment of the exposures and health impact for the use stage of building materials, using the PiF-based approach presented in this paper. As shown in our case study, PiFs and health impacts in DALYs can be calculated for different periods of the use stage, so the exposures and impacts can be considered from both a shorter-term perspective and a longer-term aspect over the entire product lifetime. Such a quantitative assessment can provide order-of-magnitude estimates for the chemical exposures and health impacts for building occupants. Finally, the most comprehensive ***third-tier*** approach would require empirical tests of the chemical emissions from the building material, and/or a full LCA which covers the manufacturing, distribution, use, and disposal stages, specifically accounts for exposures and health impact for various workers (e.g., manufacturing workers, construction workers, disposal workers, etc.), and includes other environmental and human health impacts during the entire life cycle. Since empirical tests are often performed for a relatively short duration, an LCA can complement by providing insights on the whole life cycle of the building material. These detailed third-tier assessments would provide the most accurate results to guide the selection of components and materials to manage and mitigate the use stage chemical exposures and health impacts for building materials, but it is also costly and time consuming.

The US EPA has made substantial progress in chemical characterization, including prioritizing chemicals in terms of their exposure potential (Mitchell et al. 2013a; b; Wambaugh et al. 2013), improvements to quantitative structure-activity relationships (US EPA 2017a), and databases and models for chemical ingredients in consumer products (Brandon et al. 2016; Dionisio et al. 2015; Egeghy et al. 2016; Judson et al. 2012; Wambaugh et al. 2014). These and other efforts are part of a larger effort to provide for safer and sustainable chemicals. We will continue to bridge LCA and exposure science. The research presented here is an initial step in applying these tools and lessons learned to building materials.

6 Conclusions

By reviewing the necessary steps and current practices for characterizing use stage chemical exposures and health impacts for building materials, including the methods to assess chemical emissions, exposures, and toxicological effects, the need for a scientifically defensible approach to consistently characterize use stage chemical exposures and health impacts for building materials and to integrate these impacts into LCA is identified. To meet this need, the present paper then proposes a systematic approach which builds on the PiF framework (Fantke et al. 2016) and is complemented with an improved LCI and information on human toxicity dose-response and disease severity, focusing on the use stage of building materials and impacts on building occupants. The application of the proposed approach is then illustrated by a case study of one VOC and one SVOC in particleboard products. The case study demonstrates the capability of the proposed approach to

assess the use stage chemical exposures and health impact starting from a functional unit and resulting in health impacts in DALYs, which is consistent with traditional LCA methods. The case study also shows the capability of the proposed approach to identify dominant exposure pathways and important exposure periods. The proposed approach thus provides the methodological basis for integrating into LCA the human health impacts associated with chemical exposures during the use stage of building materials. However, further developments are needed to make this approach fully operational, including the collection of chemical composition data, development of near-field exposure models, and generation of toxicity data. Several areas can also be developed to make this approach more comprehensive, such as worker exposures, complex building materials, and transformation products of the released chemicals.

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Compliance with ethical standards

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