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Fantke, Peter; Illner, Nicole

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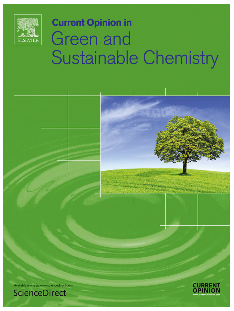

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Peter Fantke, Nicole Illner

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Goods that are good enough: Introducing an absolute sustainability perspective for managing chemicals in consumer products

Peter Fantke[1]*, Nicole Illner[1]

[1]Division for Quantitative Sustainability Assessment, Technical University of Denmark, Diplomvej 371, 2800 Kgs. Lyngby, Denmark

*Corresponding author: phone: +45 45254452, email: pefan@dtu.dk

Abstract

While many products become more sustainable, overall pressure from emissions and exposure to chemicals in products on human and environmental health increases, driven by worldwide growing chemical and product diversity and consumption. To benchmark environmental sustainability performance of new products and measure related progress, we need to move from eco-efficiency indicating relative improvements to eco-effectiveness linking chemical-related impacts to absolute sustainability limits, considering entire chemical and product life cycles. Efforts in chemical substitution and alternatives assessment to replace harmful chemicals with sustainable solutions are still in their infancy and lack applicability to product scales. Novel and innovative methods are required to understand the different life cycles, to quantify and link impacts associated with chemical-related product design decisions to actual limits for human and environmental health, and to integrate this absolute perspective in chemical substitution practice. With such methods at hand, it will be possible to develop products that are environmentally sustainable in an absolute scale.

Introduction

World population, per-capita consumption, and product diversity are continuously growing around the world. With that, also the synthesis, production and use of a growing variety of chemicals in consumer products from personal care to building materials is increasing and a main driver of global economic growth and innovation in product development. In 2013, the chemical sector required the extraction of more than 1.5 billion tonnes of fossil and refinery-based resources, and almost 1 billion tonnes of secondary reactants [1•]. This corresponds to roughly 5-10% of the resources that are extracted globally as feedstock for fueling the production and consumption of chemicals, mainly basic chemicals (e.g. plastic polymers, fertilizers, and fibers), specialty chemicals (e.g. dyes and pigments, pesticide active ingredients, and food additives), and consumer chemicals (e.g. detergents, soaps, fragrances and household chemicals) [1,2]. With that, chemicals constitute an important building block for the diversity and functionality of the wide range of our consumer products and materials. However, the use of tens of thousands commercially relevant chemicals also induces severely increasing environmental pollution and health concerns associated with chemical emissions and exposures from local to global scale [3,4]. Thereby, chemical pollution potentially arises in all stages of material and product life cycles from the chemicals and manufacturing industries utilizing the chemicals in their products and releases during the use stage, and disposal of the products in which the chemicals are used. Of special concern are exposures to hazardous chemical product constituents, such as certain metals, highly fluorinated compounds, flame-retardants, antimicrobial agents, bisphenols, phthalates, and certain solvents that are found in a variety of daily consumer goods [4-6•]. Efficient, effective and innovative approaches in chemical substitution are required more than ever to overcome this unsustainable and increasingly unmanageable trend related to chemicals.

In order to address this challenge, the United Nations' Global Environmental and Chemical Outlooks [2,7], the OECD's Environmental Strategy and Outlook [8,9], and the Europe's Non-Toxic Environment Strategy [10•] all declare an urgent need for much greater reduction of harmful chemicals in products. However, methodologies to effectively reduce chemical emissions and exposures at the global level are still lacking, rendering chemical pollution still one of the main concerns related to impacts on human health [11] and on ecosystem functioning [12]. Instead, most environmental sustainability-related efforts focus on relative (and often marginal if at all any) improvements per product unit, while the number of product units is steadily increasing—ultimately further fostering a production trend that is unsustainable for our global environment [13••,14].

Yet, what is sustainable enough and how can we achieve it? To answer these questions in support of developing actually (i.e. absolutely) sustainable products, we need to address three main aspects and relate relevant sustainability assessment efforts in chemical substitution and alternatives assessment, where viable alternatives to harmful chemicals in products and processes are identified and evaluated. First, we need to understand the complex interaction of chemical and product life cycles, and quantify all environmental impacts associated with the use of chemicals. Second, we need to identify the right environmental sustainability targets based on human and ecological health capacities, and define metrics that allow us to measure progress toward meeting these targets, thereby considering product-, company-, and region-specific boundary conditions. Third and last, we need to develop comprehensive and informative approaches for chemical substitution used by practitioners and product designers for successfully identifying viable solutions that can serve as absolute environmentally sustainable alternatives to currently used harmful chemicals in products [6]. In the following, we discuss the way forward for addressing these three aspects to pave a possible road toward products that are ‘good enough’, i.e. environmentally sustainable in absolute terms, with first focus on environmental sustainability.

From chemical to product life cycles and their environmental sustainability

Chemicals are intimately linked to the societal services provided by products and materials, since they fulfill specific performance functions as basic material constituents and formulation ingredients. Furthermore, chemicals are used for auxiliary processes required along the wider realm of product life cycles, such as extraction, processing, or removal agents. Hence, a life cycle perspective is necessary in any chemical substitution and alternatives assessment context in order to identify and minimize exposure of humans and ecosystems to harmful chemicals along consumer product life cycles [15,16]. This perspective is well aligned with the circular economy, where it is mostly applied to optimize resource efficiency and waste handling [17], while the optimization of chemical-related impacts that predominantly occur before a product’s end-of-life stage are just recently gaining attention. Applying a life cycle perspective, however, requires to clearly differentiating the life cycle of a chemical—the focus of the European REACH regulation [18]—from the life cycle of a product or product system. While tens to hundreds of chemicals are usually involved in a product life cycle, a chemical, polymer or material can also enter several product life cycles through e.g. increased recycling of polymer waste (Figure 1).

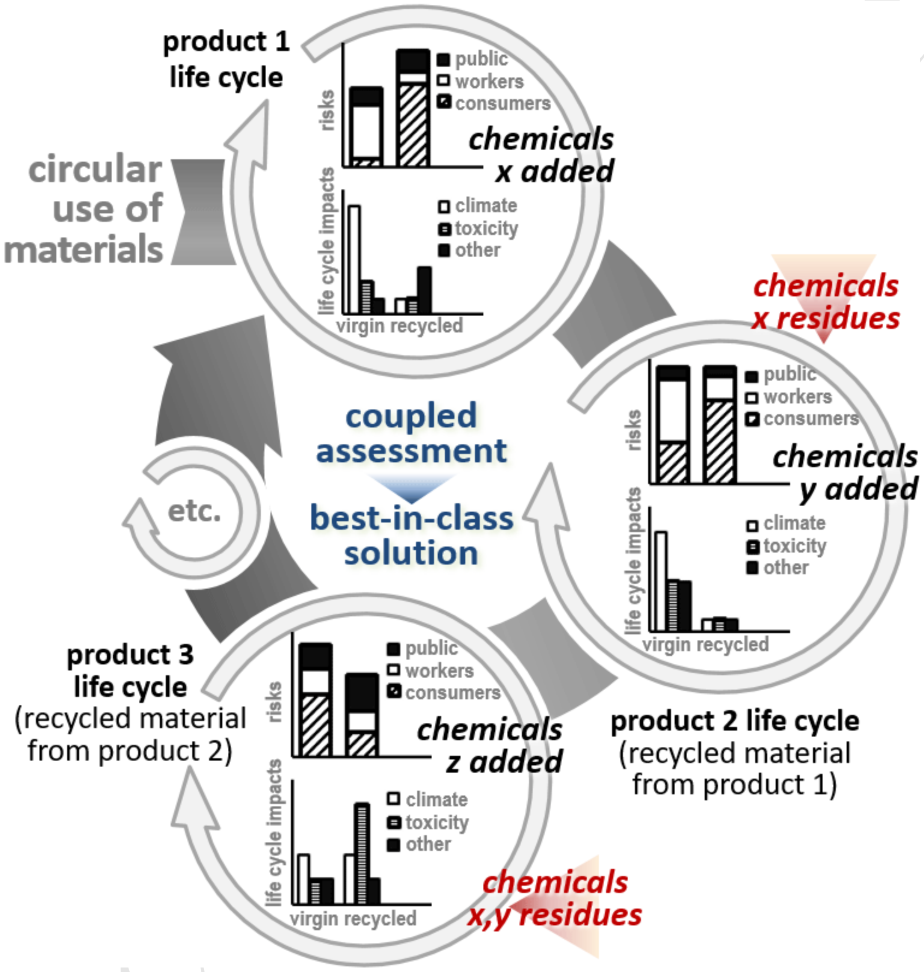

Figure 1. Assessment framework for alternative materials entering multiple product life cycles, where elements from safety and from sustainability assessment are coupled in a consistent way using comparative and quantitative metrics to identify and minimize trade-offs long the entire chemical life cycle and value chain.

Increasing diversity of marketed chemicals in consumer products along with the complexity of product compositions and supply chains on the one hand, and the growing need for a sustainable society on the other hand require a clear definition of interfaces between chemical, material, and product life cycles. In this context, evaluating chemical or material life cycles that span over several product life cycles comes with challenges that are not yet fully understood. One often-discussed challenge is cross-contamination from toxic residues. Recent studies have shown that hazardous chemical residues are found in recycled food contact materials [19,20], but also in other products containing recycled materials, such as children's toys [21] or other plastics [22]. There is a need to include cross-contamination as potential trade-off when designing a recyclable product. More generally, the concept of a circular economy can only be successful, if we are able to incorporate in product design decisions all relevant optimization requirements for different levels of circularity. For reuse, this includes to assess increased exposure duration versus reduced resources extraction. For recycling, the introduction of cross-contamination, potentially increased exposures and new exposure settings to residual chemicals in recycled materials (see Figure 1), and increased energy, water and resources use for additional recycling processes versus decrease in resources extraction should be assessed. For repairing, it is relevant to address increased energy, water and material use for spare parts and repair work versus decrease in resource extraction and waste. For remanufacturing, this includes assessing increased exposure to additional materials versus decrease in manufacturing energy use and waste. A sustainable way out of the challenges around the use of harmful chemicals in products, especially in a circular economy context, should not only be restricted to analyze the option of using drop-in chemicals as potential alternatives (i.e. structurally similar chemicals), which may yield similarly harmful or unsustainable performance. Instead, for successfully addressing these challenges, we also need to explore technical (e.g. new barriers in packaging materials to reduce migration into food matrices) and conceptual (e.g. safe-by-design) solutions. In this context, it is important to look beyond particular hazards or exposure conditions.

When addressing harmful chemicals in products in a regulatory context, occupational, consumer, population and even ecological exposures and hazards are separately considered [18,23,24], while potential trade-offs among them and with environmental sustainability impacts along the entire related product life cycle are ignored. However, only when both specific risks and sustainability impacts are addressed together for each product life cycle as illustrated in Figure 1, we are able to avoid shifting the burden from one aspect or region to another in our attempt to identify viable solutions in chemical substitution and alternatives assessment [25]. Applying this to the thousands of chemicals currently in commerce is not a simple task and requires prioritization of the most contributing chemicals and impacts along the considered life cycles [26]. However, even when considering all trade-offs, how can we ensure that the proposed product solutions are good enough? For that, it is in principle necessary to identify chemical exposure and pollution benchmark targets and define for each target a limit, beyond which a product is not sustainable anymore [27••].

Identifying absolute sustainability targets for chemicals and measuring related progress

Several targets defined in the United Nations' Sustainable Development Goals are related to reducing chemical pollution and exposure by 2020 or 2030 [28]. These targets can be used to benchmark emission and exposure levels. At the global scale, another conceptual framework can be used for benchmarking, namely the planetary boundaries, which indicate a 'safe operating space' for our society [29]. However, local-to-regional boundaries still need to be identified, and control variables for specifying a 'safe operating space' for chemical pollution remain to be defined [30]. Such control variables should for ecosystems be rooted in ecological carrying capacities that define benchmark exposure levels below which ecosystems are not irreversibly damaged [31•], and for humans in the capacity of nations to avoid human disease burden based on improving the availability, accessibility and quality of health care [32•].

While targets can be defined based on different reference points, methods for allocating these targets to the performance of a particular product or product system also need to be developed, accounting for the overall production quantity and regional differences in related ecological carrying capacities. Assessing sustainability at product level (and not just at the level of nations, cities or companies) is important, since it is not straightforward to go from the global level to the product level and a number of assumptions and choices are required to properly scale down sustainability impacts as well as related carrying capacities and allocate both to individual products. Product-level sustainability assessment could help both companies to decide what is needed in terms of improvement of specific products and consumers to judge the types and level of consumption that can be considered sustainable [33]. Linking ecological carrying capacities to absolute sustainability targets is an emerging research field, starting with a seminal paper on gauging industrial sustainability [13], followed since by a series of about 20-30 studies linking life cycle impacts to planetary boundaries and other absolute sustainability targets [34-37]. This research indicates that environmental impacts of economic activities need to be aligned with the continuous functioning of the life-sustaining services of nature, i.e. we need to reduce unit resource consumption and environmental emissions and exposure to an extent that allows us to stay within an actually sustainable space, i.e. within a ‘safe operating space’.

This is illustrated in Figure 2, where for any product or product system **A** the different environmental impacts **(1)** and **(2)** are quantified (left bars) that cumulatively exceed a related absolute sustainability target (dashed horizontal line), and where a design choice leads to product or product system **B** (right bars) with its different cumulative impacts. Three archetypal scenarios are possible. First, impacts in each category (e.g. human toxicity, air pollution, ecotoxicity) change but both products exceed absolute targets, which usually comes with shifting the burden from one impact category to another (Figure 2, top plot). Second, impacts in one or more categories are reduced while others remain constant, leading cumulatively to overall impact reduction without burden shifting, which still exceeds (to a lesser extent now) absolute targets (Figure 2, middle plot). Third, impacts in one or more categories are reduced without burden shifting and cumulatively to the extent that absolute targets are met (Figure 2, bottom plot). The last scenario is the only one that will ultimately lead to absolutely sustainable products and is hence the only desirable scenario in line with sustainability goals.

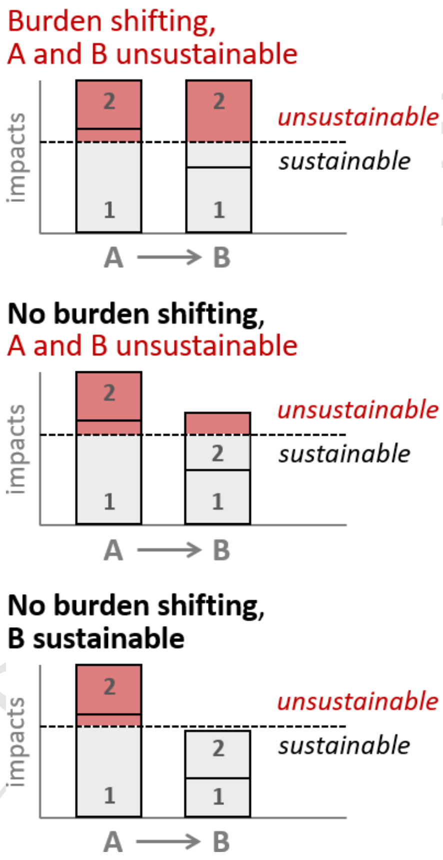

Figure 2. Illustration of different scenarios of burden shifting between impacts or life cycle stages or regions (1) and (2) and relation to absolute sustainability targets between product solutions or product design choices (A) and (B). An example for such burden shifting is to replace a harmful chemical in a consumer product to reduce consumer risk, while the substitute has a more complex synthesis, thus leading to higher manufacturing energy use and related emissions (top and middle graphs). In this example, the original harmful chemical

would need to be replaced by an alternative that does also not lead to increased environmental impacts in manufacturing in order to become sustainable (bottom graph).

When absolute sustainability targets are defined, the related performance of designed products or product systems needs to be quantified and compared against these targets in order to identify whether a design choice or one of its alternatives stays within the sustainability domain (see Figure 2). For that, both quantifiable sustainability performances and related absolute targets need to be considered in chemical substitution and alternatives assessment frameworks that are applied by product designers and other decision makers to evaluate different alternatives and identify the ‘best-in-class’ solution. How are these aspects considered in chemical substitution and alternatives assessment practice today? In the following section, we discuss this question.

Alternatives assessment: Solutions for substituting harmful chemicals in products

Currently, environmental sustainability aspects are mostly considered as secondary goal and late in the technology readiness stages [38], whereas assessing related trade-offs and measuring performance against absolute targets will have the highest effect at early product design stages. To evaluate ‘best-in-class’ options among various alternatives at early design stages, alternatives assessment and chemical substitution are ideal rapid-screening level tools [6,39], which ideally compare alternatives to harmful chemicals in products and processes based on a common function or societal service [40•]. Existing alternatives assessment frameworks, however, focus mostly on hazard, and technical and economic feasibility, while environmental sustainability aspects and an absolute perspective are not considered. This renders current assessment results unable to support chemical and product design in relation to any environmental sustainability targets. Moreover, current alternatives assessment practice mostly relies on qualitative or categorical metrics [41,42]. However, to successfully minimize trade-offs and measure performance progress against absolute sustainability targets, comparative metrics (to allow for comparison of environmental sustainability impacts and their respective absolute targets) and quantitative yet rapid-screening assessment approaches are required (to allow for quantitatively identifying and minimizing tradeoffs e.g. in exposure settings) [42,43].

Using such approaches, specific exposure settings for workers and consumers need to be consistently combined with population exposures from environmental life cycle emissions and related absolute targets. This is important in order to go beyond marginal improvements in product design, which could result from improving a certain exposure aspect, while introducing additional exposure elsewhere along the product's life cycle. As promising approach introducing comparative metrics and quantitative, rapid-screening level assessment, a high-throughput framework has been recently proposed that on the one hand integrates different exposures and populations, while on the other hand being compatible with the alternatives assessment framework [44••,45]. This exposure assessment framework has been applied to screen different alternatives to chemicals in cosmetics [46], food contact materials [47], personal care products [48], and building materials [49], and can be expanded based on models to cover additional product types [50]. Along with additional models, also exposure and hazard data are required for all considered alternatives, be it chemicals or other solutions, such as of material, technological, or behavioral nature. However, this constitutes a current challenge, since for example adequate exposure-response information is available usually only for a handful of well-studied chemicals [51], while largely missing for most of less-studied chemicals in global commerce and hence also missing in estimates of human disease burden. Promising solutions to be explored are high-throughput methods to screen exposure [52•] and toxicity across a wide range of chemicals [53•].

Aforementioned efforts provides a first stepping stone for combining chemical-related assessments with absolute targets for environmental sustainability. While in this context, the limited capacity of our sustaining ecological and health systems is already widely acknowledged [54-59], quantitative metrics for absolute targets and for measuring related progress toward meeting these targets still need to be developed. In support of such metrics, some studies relate chemical pollution to regulatory concentration thresholds [60-63], but these do usually not reflect actual and regionally varying carrying capacities. Hence, while first attempts to link absolute sustainability targets to product life cycles exist, further efforts are required to systematically developing methods for introducing an absolute perspective also in alternatives assessment and green chemistry.

Conclusions

While products are becoming more sustainable, we also need to reduce overall chemical-related pressure on human and environmental health. This requires moving from relative and marginal improvements as assessed in current life cycle assessments to applying an absolute sustainability perspective that allows measuring progress toward relevant limits for chemical pollution and exposure at various scales. Chemical substitution and alternatives assessment to replace harmful chemicals with sustainable solutions are emerging and promising frameworks, into which an absolute sustainability perspective should be introduced. This requires a deep understanding of the complex interaction of different chemical, material and product life cycles, novel methods to quantify and link chemical-related impacts to actual limits for human and environmental health, and to integrate these methods in chemical substitution practice. Once such methods are becoming available, it will be possible to develop products that are environmentally sustainable in an absolute scale, i.e. designing and developing goods that are good enough.

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