



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

Fantke, Peter; Illner, Nicole

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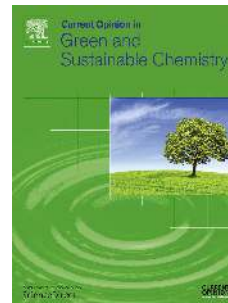
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# Accepted Manuscript

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Peter Fantke, Nicole Illner



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

3 Peter Fantke<sup>1\*</sup>, Nicole Illner<sup>1</sup>

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5 <sup>1</sup>Division for Quantitative Sustainability Assessment, Technical University of Denmark,  
6 Diplomvej 371, 2800 Kgs. Lyngby, Denmark

7

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

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10

**11 Abstract**

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

**26 Introduction**

27 World population, per-capita consumption, and product diversity are continuously  
28 growing around the world. With that, also the synthesis, production and use of a growing  
29 variety of chemicals in consumer products from personal care to building materials is  
30 increasing and a main driver of global economic growth and innovation in product  
31 development. In 2013, the chemical sector required the extraction of more than 1.5 billion  
32 tonnes of fossil and refinery-based resources, and almost 1 billion tonnes of secondary  
33 reactants [1•]. This corresponds to roughly 5-10% of the resources that are extracted globally  
34 as feedstock for fueling the production and consumption of chemicals, mainly basic chemicals  
35 (e.g. plastic polymers, fertilizers, and fibers), specialty chemicals (e.g. dyes and pigments,  
36 pesticide active ingredients, and food additives), and consumer chemicals (e.g. detergents,

37 soaps, fragrances and household chemicals) [1,2]. With that, chemicals constitute an  
38 important building block for the diversity and functionality of the wide range of our consumer  
39 products and materials. However, the use of tens of thousands commercially relevant  
40 chemicals also induces severely increasing environmental pollution and health concerns  
41 associated with chemical emissions and exposures from local to global scale [3,4]. Thereby,  
42 chemical pollution potentially arises in all stages of material and product life cycles from the  
43 chemicals and manufacturing industries utilizing the chemicals in their products and releases  
44 during the use stage, and disposal of the products in which the chemicals are used. Of special  
45 concern are exposures to hazardous chemical product constituents, such as certain metals,  
46 highly fluorinated compounds, flame-retardants, antimicrobial agents, bisphenols, phthalates,  
47 and certain solvents that are found in a variety of daily consumer goods [4-6]. Efficient,  
48 effective and innovative approaches in chemical substitution are required more than ever to  
49 overcome this unsustainable and increasingly unmanageable trend related to chemicals.

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

60 Yet, what is sustainable enough and how can we achieve it? To answer these questions  
61 in support of developing actually (i.e. absolutely) sustainable products, we need to address  
62 three main aspects and relate relevant sustainability assessment efforts in chemical

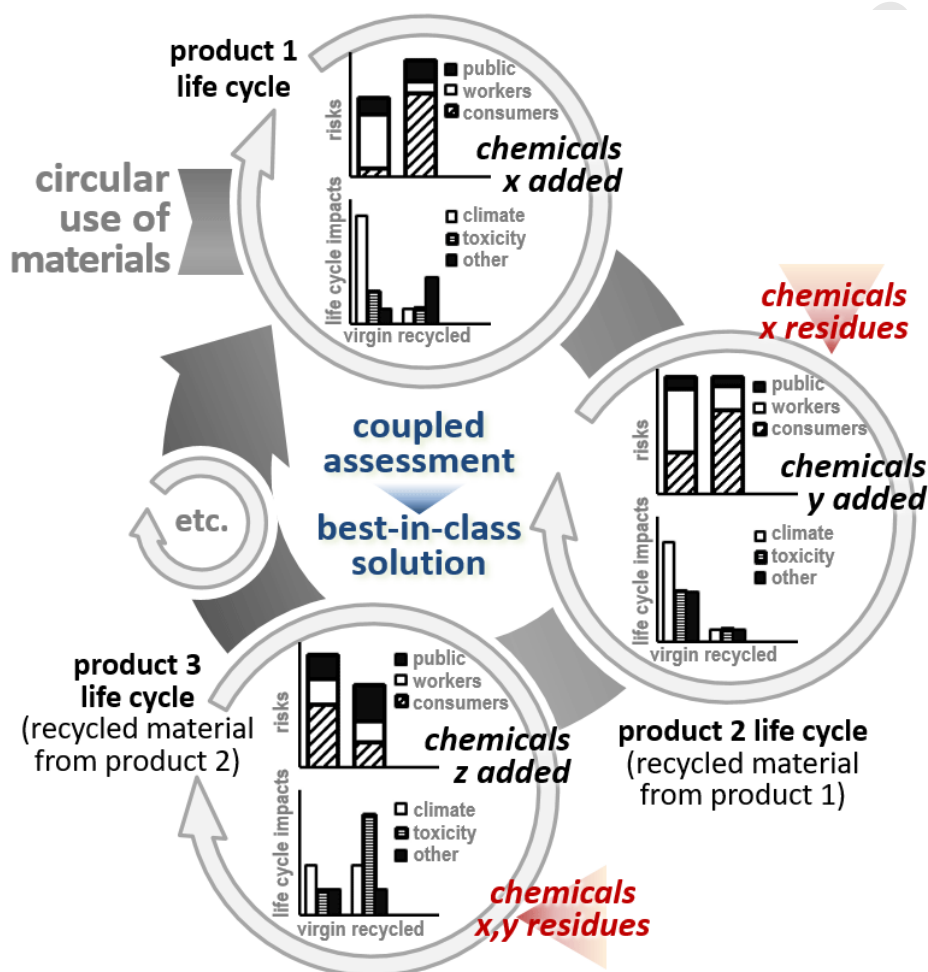
63 substitution and alternatives assessment, where viable alternatives to harmful chemicals in  
64 products and processes are identified and evaluated. First, we need to understand the complex  
65 interaction of chemical and product life cycles, and quantify all environmental impacts  
66 associated with the use of chemicals. Second, we need to identify the right environmental  
67 sustainability targets based on human and ecological health capacities, and define metrics that  
68 allow us to measure progress toward meeting these targets, thereby considering product-,  
69 company-, and region-specific boundary conditions. Third and last, we need to develop  
70 comprehensive and informative approaches for chemical substitution used by practitioners  
71 and product designers for successfully identifying viable solutions that can serve as absolute  
72 environmentally sustainable alternatives to currently used harmful chemicals in products [6].  
73 In the following, we discuss the way forward for addressing these three aspects to pave a  
74 possible road toward products that are ‘good enough’, i.e. environmentally sustainable in  
75 absolute terms, with first focus on environmental sustainability.

76

### 77 **From chemical to product life cycles and their environmental sustainability**

78 Chemicals are intimately linked to the societal services provided by products and  
79 materials, since they fulfill specific performance functions as basic material constituents and  
80 formulation ingredients. Furthermore, chemicals are used for auxiliary processes required  
81 along the wider realm of product life cycles, such as extraction, processing, or removal  
82 agents. Hence, a life cycle perspective is necessary in any chemical substitution and  
83 alternatives assessment context in order to identify and minimize exposure of humans and  
84 ecosystems to harmful chemicals along consumer product life cycles [15,16]. This perspective  
85 is well aligned with the circular economy, where it is mostly applied to optimize resource  
86 efficiency and waste handling [17], while the optimization of chemical-related impacts that  
87 predominantly occur before a product’s end-of-life stage are just recently gaining attention.  
88 Applying a life cycle perspective, however, requires to clearly differentiating the life cycle of

89 a chemical—the focus of the European REACH regulation [18]—from the life cycle of a  
 90 product or product system. While tens to hundreds of chemicals are usually involved in a  
 91 product life cycle, a chemical, polymer or material can also enter several product life cycles  
 92 through e.g. increased recycling of polymer waste (Figure 1).  
 93



94  
 95 Figure 1. Assessment framework for alternative materials entering multiple product life  
 96 cycles, where elements from safety and from sustainability assessment are coupled in a  
 97 consistent way using comparative and quantitative metrics to identify and minimize trade-offs  
 98 long the entire chemical life cycle and value chain.

99  
 100 Increasing diversity of marketed chemicals in consumer products along with the  
 101 complexity of product compositions and supply chains on the one hand, and the growing need

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



127           When addressing harmful chemicals in products in a regulatory context, occupational,  
128 consumer, population and even ecological exposures and hazards are separately considered  
129 [18,23,24], while potential trade-offs among them and with environmental sustainability  
130 impacts along the entire related product life cycle are ignored. However, only when both  
131 specific risks and sustainability impacts are addressed together for each product life cycle as  
132 illustrated in Figure 1, we are able to avoid shifting the burden from one aspect or region to  
133 another in our attempt to identify viable solutions in chemical substitution and alternatives  
134 assessment [25]. Applying this to the thousands of chemicals currently in commerce is not a  
135 simple task and requires prioritization of the most contributing chemicals and impacts along  
136 the considered life cycles [26]. However, even when considering all trade-offs, how can we  
137 ensure that the proposed product solutions are good enough? For that, it is in principle  
138 necessary to identify chemical exposure and pollution benchmark targets and define for each  
139 target a limit, beyond which a product is not sustainable anymore [27••].

140

#### 141 **Identifying absolute sustainability targets for chemicals and measuring related progress**

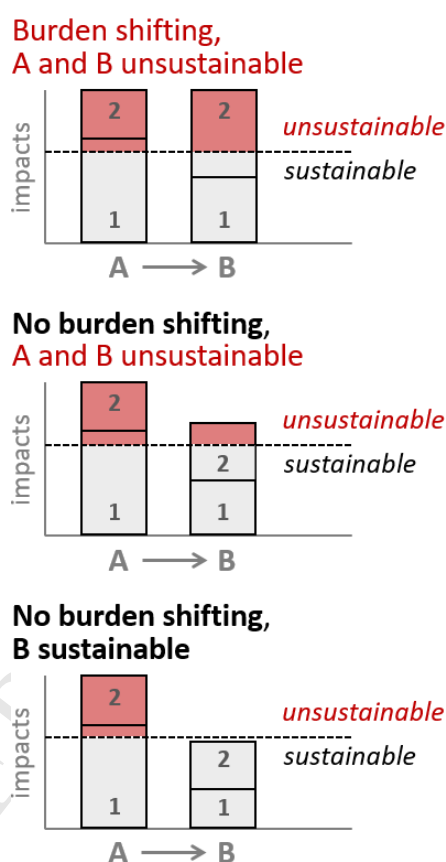
142           Several targets defined in the United Nations' Sustainable Development Goals are  
143 related to reducing chemical pollution and exposure by 2020 or 2030 [28]. These targets can  
144 be used to benchmark emission and exposure levels. At the global scale, another conceptual  
145 framework can be used for benchmarking, namely the planetary boundaries, which indicate a  
146 'safe operating space' for our society [29]. However, local-to-regional boundaries still need to  
147 be identified, and control variables for specifying a 'safe operating space' for chemical  
148 pollution remain to be defined [30]. Such control variables should for ecosystems be rooted in  
149 ecological carrying capacities that define benchmark exposure levels below which ecosystems  
150 are not irreversibly damaged [31•], and for humans in the capacity of nations to avoid human  
151 disease burden based on improving the availability, accessibility and quality of health care  
152 [32•].

153 While targets can be defined based on different reference points, methods for  
154 allocating these targets to the performance of a particular product or product system also need  
155 to be developed, accounting for the overall production quantity and regional differences in  
156 related ecological carrying capacities. Assessing sustainability at product level (and not just at  
157 the level of nations, cities or companies) is important, since it is not straightforward to go  
158 from the global level to the product level and a number of assumptions and choices are  
159 required to properly scale down sustainability impacts as well as related carrying capacities  
160 and allocate both to individual products. Product-level sustainability assessment could help  
161 both companies to decide what is needed in terms of improvement of specific products and  
162 consumers to judge the types and level of consumption that can be considered sustainable  
163 [33]. Linking ecological carrying capacities to absolute sustainability targets is an emerging  
164 research field, starting with a seminal paper on gauging industrial sustainability [13], followed  
165 since by a series of about 20-30 studies linking life cycle impacts to planetary boundaries and  
166 other absolute sustainability targets [34-37]. This research indicates that environmental  
167 impacts of economic activities need to be aligned with the continuous functioning of the life-  
168 sustaining services of nature, i.e. we need to reduce unit resource consumption and  
169 environmental emissions and exposure to an extent that allows us to stay within an actually  
170 sustainable space, i.e. within a 'safe operating space'.

171 This is illustrated in Figure 2, where for any product or product system **A** the different  
172 environmental impacts **(1)** and **(2)** are quantified (left bars) that cumulatively exceed a related  
173 absolute sustainability target (dashed horizontal line), and where a design choice leads to  
174 product or product system **B** (right bars) with its different cumulative impacts. Three  
175 archetypal scenarios are possible. First, impacts in each category (e.g. human toxicity, air  
176 pollution, ecotoxicity) change but both products exceed absolute targets, which usually comes  
177 with shifting the burden from one impact category to another (Figure 2, top plot). Second,  
178 impacts in one or more categories are reduced while others remain constant, leading

179 cumulatively to overall impact reduction without burden shifting, which still exceeds (to a  
 180 lesser extent now) absolute targets (Figure 2, middle plot). Third, impacts in one or more  
 181 categories are reduced without burden shifting and cumulatively to the extent that absolute  
 182 targets are met (Figure 2, bottom plot). The last scenario is the only one that will ultimately  
 183 lead to absolutely sustainable products and is hence the only desirable scenario in line with  
 184 sustainability goals.

185



186

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

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

195

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

205

### 206 **Alternatives assessment: Solutions for substituting harmful chemicals in products**

207 Currently, environmental sustainability aspects are mostly considered as secondary  
208 goal and late in the technology readiness stages [38], whereas assessing related trade-offs and  
209 measuring performance against absolute targets will have the highest effect at early product  
210 design stages. To evaluate ‘best-in-class’ options among various alternatives at early design  
211 stages, alternatives assessment and chemical substitution are ideal rapid-screening level tools  
212 [6,39], which ideally compare alternatives to harmful chemicals in products and processes  
213 based on a common function or societal service [40]. Existing alternatives assessment  
214 frameworks, however, focus mostly on hazard, and technical and economic feasibility, while  
215 environmental sustainability aspects and an absolute perspective are not considered. This  
216 renders current assessment results unable to support chemical and product design in relation  
217 to any environmental sustainability targets. Moreover, current alternatives assessment practice  
218 mostly relies on qualitative or categorical metrics [41,42]. However, to successfully minimize

219 trade-offs and measure performance progress against absolute sustainability targets,  
220 comparative metrics (to allow for comparison of environmental sustainability impacts and  
221 their respective absolute targets) and quantitative yet rapid-screening assessment approaches  
222 are required (to allow for quantitatively identifying and minimizing tradeoffs e.g. in exposure  
223 settings) [42,43].

224 Using such approaches, specific exposure settings for workers and consumers need to  
225 be consistently combined with population exposures from environmental life cycle emissions  
226 and related absolute targets. This is important in order to go beyond marginal improvements  
227 in product design, which could result from improving a certain exposure aspect, while  
228 introducing additional exposure elsewhere along the product's life cycle. As promising  
229 approach introducing comparative metrics and quantitative, rapid-screening level assessment,  
230 a high-throughput framework has been recently proposed that on the one hand integrates  
231 different exposures and populations, while on the other hand being compatible with the  
232 alternatives assessment framework [44•,45]. This exposure assessment framework has been  
233 applied to screen different alternatives to chemicals in cosmetics [46], food contact materials  
234 [47], personal care products [48], and building materials [49], and can be expanded based on  
235 models to cover additional product types [50]. Along with additional models, also exposure  
236 and hazard data are required for all considered alternatives, be it chemicals or other solutions,  
237 such as of material, technological, or behavioral nature. However, this constitutes a current  
238 challenge, since for example adequate exposure-response information is available usually  
239 only for a handful of well-studied chemicals [51], while largely missing for most of less-  
240 studied chemicals in global commerce and hence also missing in estimates of human disease  
241 burden. Promising solutions to be explored are high-throughput methods to screen exposure  
242 [52•] and toxicity across a wide range of chemicals [53•].

243 Aforementioned efforts provides a first stepping stone for combining chemical-related  
244 assessments with absolute targets for environmental sustainability. While in this context, the

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

253

## 254 **Conclusions**

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

268

## 269 **Acknowledgements**

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271

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