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1 **Value choices in life cycle impact assessment of stressors causing human health**  
2 **damage**

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1 <heading level 1> Abstract

2 This article investigates how value choices in life cycle impact assessment can influence  
3 characterization factors (CFs) for human health (expressed as disability-adjusted life years or  
4 DALY). The Cultural Theory is used to define sets of value choices in the calculation of CFs,  
5 reflecting the individualist, hierarchist and egalitarian perspectives. CFs were calculated for  
6 interventions related to the impact categories water scarcity, tropospheric ozone formation,  
7 particulate matter formation, human toxicity, ionizing radiation, stratospheric ozone depletion and  
8 climate change.

9 With the Cultural Theory as a framework, we show that individual, hierarchical and egalitarian  
10 perspectives can lead to CFs that vary up to six orders of magnitude. For persistent substances, the  
11 choice in time horizon explains the differences among perspectives, while for non-persistent  
12 substances, the choice in age weighting and discount rate of DALY, and the type of effects or  
13 exposure routes, accounts for differences in CFs. The calculated global impact varies by two orders  
14 of magnitude, depending on the perspective selected and derives mainly from particulate matter  
15 formation and water scarcity for the individualist perspective, and from climate change for the  
16 egalitarian perspective.

17 Our results stress the importance of dealing with value choices in life cycle impact assessment and  
18 suggest further research for analyzing the practical consequences for life cycle assessment results.

19

20 Keywords

21 uncertainty analysis

22 value choices

23 life cycle impact assessment

24 human health

25 Cultural Theory

26

1 <heading level 1> Introduction

2 Uncertainties are inevitable in life cycle assessment (LCA), risk assessment, or any other analytical  
3 tool to assess environmental impacts (e.g., Huijbregts, 1998, Steen, 2006). Different types of  
4 uncertainty arise within each step of an assessment — for example, while collecting data, defining  
5 system boundaries, or calculating environmental impacts of emissions.

6 Several typologies are put forward to describe the different types of uncertainty (e.g., Morgan and  
7 Henrion, 1990, Wynne, 1992, van Asselt and Rotmans, 2002, Ascough et al., 2008). In general,  
8 three types of uncertainties can be distinguished: measurement uncertainty, uncertainty from  
9 assumptions and uncertainty from ignorance. In this paper we focus on uncertainties from  
10 assumptions in life cycle impact assessment. Uncertainties from assumptions most often involve  
11 value choices. Assumptions can derive from lack in knowledge, whereby the choice of one option  
12 above another can be influenced by personal values such as, what is commonly accepted or  
13 familiarity. Hertwich et al. (2000) describe these value choices as contextual values. On the other  
14 hand, assumptions can also be driven by personal beliefs and values that reflect what we care about,  
15 without any science being involved. A typical example is the equity of different age groups or  
16 species. These value choices are defined as preference values (Hertwich et al., 2000).

17 Scenario analyses can be used to investigate the uncertainties related to assumptions or choices that  
18 reflect different personal values. Several tools and frameworks exist to cluster different personal  
19 values and define model scenarios (e.g., Schwartz and Mark, 1992, Tukker, 2002). Within LCA, the  
20 Cultural Theory has been used as a tool, as it both reflects visions on society and views on nature  
21 (e.g., Hofstetter, 1998, Frischknecht et al., 2000, Goedkoop et al., 2008). The Cultural Theory  
22 distinguishes five different perspectives from which people perceive the world and behave in it.  
23 Three of these are generally used within environmental decision making: the individualist,  
24 hierarchist and egalitarian perspectives (Hofstetter, 1998, Hofstetter et al., 2000). Each perspective  
25 reflects a hypothetical stakeholder or decision maker with a specific set of preferences and  
26 contextual values that explains one's view on society and nature (Schwarz and Thompson, 1990,

1 Thompson et al., 1990, van Asselt and Rotmans, 1996). Several case studies have empirically  
2 shown a relationship between cultural perspectives and environmental concerns (e.g., Steg and  
3 Sievers, 2000, Lima and Castro, 2005, Leiserowitz, 2006). An analysis of the toxicity controversy  
4 in Sweden and the Netherlands indicates that within the specific study the individualist perspective  
5 has a link with opinions from industry, the hierarchist perspective with the Environmental  
6 Protection Agency (in Sweden) or the Dutch environmental ministry and the egalitarian perspective  
7 with environmentalists (Tukker et al., 2002). Therefore, the Cultural theory is recognized in (partly)  
8 contributing to a better understanding of different environmental perceptions.

9 Most impact assessment methodologies embed value choices without giving practitioners or  
10 decision makers the opportunity to assess the difference in result when applying a distinct world  
11 view (e.g., Jolliet et al., 2003, Hauschild and Potting, 2005). Some impact assessment  
12 methodologies do handle uncertainties arising from value choices by applying the Cultural Theory,  
13 but in a limited and not always consistent way (e.g., Goedkoop et al., 2008). Therefore, we argue  
14 for broader implementation of the Cultural Theory in an impact assessment methodology that  
15 combines several impact categories. In this case, each scenario basically reflect the choices made in  
16 the modeling using one specific line of reasoning throughout the analysis.

17 The goal of this paper is to address uncertainties related to assumptions and value choices in life  
18 cycle impact assessment. Three sets of characterization factors (CFs) for human health damage  
19 (expressed as disability-adjusted life years or DALYs) are developed, by implementing specific  
20 value choices for the individualist, hierarchist and egalitarian perspectives in existing impact  
21 assessment models. For each perspective, we defined value choices for seven human health impact  
22 categories: water scarcity, tropospheric ozone formation, particulate matter formation, human  
23 toxicity, ionizing radiation, stratospheric ozone depletion, and climate change. These categories  
24 address both local and global effects as well as short- and long-term effects, and are the most widely  
25 used environmental impact categories in life cycle assessment of human health (Hauschild et al.,  
26 2009). Our work focuses on human health damage, but is equally relevant to analyze impacts for

1 ecosystem quality and resource depletion. The value choices recognized as main drivers for  
2 differences in CFs among perspectives are outlined and explained. The constructed impact  
3 assessment methodology is used to quantify the human health damage from annual global water  
4 consumption and outdoor emissions, and to analyze the differences among perspectives. Finally, the  
5 limitations of the analysis and future research needs are discussed.

6

## 7 <heading level 1> Methodology

### 8 <heading level 2> Value choices

9 The individualist, hierarchist and egalitarian perspectives each have their own contextual and  
10 preference values (Schwarz and Thompson, 1990, Hofstetter et al., 2000, Jager et al., 1997,  
11 Thompson et al., 1990, van Asselt and Rotmans, 1996). The individualist perspective is characterized  
12 by weak group cohesions (relationships) and regulations for social relations, and considers nature to  
13 be stable and able to recover from any disturbance. This coincides with the view that humans have a  
14 high adaptive capacity through technological and economic development. Known damages are  
15 considered as the most reliable basis for decisions and present effects are emphasized over future  
16 gains or losses. The hierarchist perspective is characterized by strong group cohesion with binding  
17 regulations for social relations and considers nature to be in equilibrium. This perspective coincides  
18 with the view that impacts can be avoided with proper management and the search for a balance  
19 between manageability and the precautionary principle. The egalitarian perspective has strong group  
20 cohesion coupled with few regulations and considers nature to be fragile and unstable. This vision  
21 gives high priority to the precautionary principle and equal importance to present and future effects.

22 Figure 1 presents an overview of the different contextual and preference values, projected along the  
23 cause effect pathway. For seven human health impact categories, existing damage models that  
24 calculate CFs were adapted to the three sets of value choices. The damage models selected are those  
25 included in ReCiPe 2008 (Goedkoop et al., 2008) with water scarcity added as extra impact category

1 (Pfister et al., 2009) and updated characterization factors for climate change (De Schryver et al.,  
2 2009). An exception holds for the impact category stratospheric ozone depletion, as it was not  
3 feasible to include time horizon specific calculations in the model employed in ReCiPe2008 (Struijs  
4 et al., 2010). For this impact category, the model developed by Hajashi et al. (2006) was adapted.  
5 Table 1 is a synopsis of the choices that are used in the calculations. For detailed descriptions see  
6 appendix 1 (table 1).

7 Preference values reflect what we care about, our moral values and ideas of what is good or bad for  
8 society, such as the concern for equity or future generations (Munthe, 1997, Hertwich et al., 2000).

9 The following choices regarding different preferences were considered:

- 10 • The temporal vision of life and society is perspective-dependent (Jager et al., 1997). Time  
11 perspective can be applied by considering effects within a certain time horizon or by  
12 discounting future effects. Different time horizons were applied within the calculation from  
13 emission to effect, while discounting was applied to calculate the damage, namely  
14 discounting years of life lost in the future (Murray and Lopez, 1996, Hellweg et al., 2003).  
15 Based on Jager et al. (1997) and Janssen and Rotmans (1995), we selected a time horizon of  
16 20 years and a discount rate of 5% for the individualist perspective, emphasizing present and  
17 short-term effects. The hierarchist perspective has a more balanced time perspective and  
18 follows a 100-year time horizon, which is most frequently used by several organizations  
19 (ISO/TR14047:2003, 2003, Steinfeld et al., 2006, PAS 2050, 2008). We propose a 3%  
20 discount rate, as this rate is used as default scenario in burden of disease calculations by the  
21 World Health Organization (Murray and Lopez, 1996). The egalitarian perspective gives  
22 importance to long-term effects as current and future effects are considered equal. This  
23 coincides with an infinite time horizon and 0% discount rate (Jager et al., 1997, Janssen and  
24 Rotmans, 1995).

1 • Assigning value to a year of life at different ages (defined as age weighting) depends on  
2 personal preference (Murray and Lopez, 1996). The individualist perspective gives a higher  
3 value to more economically relevant subpopulations. The strong group cohesion of the  
4 hierarchist and egalitarian perspectives results in equality and thus no differentiation between  
5 individuals of different ages (Hofstetter, 1998).

6 • Including or excluding positive effects can be considered as a preference value choice (Jager  
7 et al., 1997). Examples of positive environmental effects are the cooling effects from  
8 chlorofluorocarbons and halons that counter climate change, as well as nitrogen oxides that  
9 degrade tropospheric ozone, countering ozone formation. Positive effects were only included  
10 for the individualist perspective following their positive attitude towards environmental  
11 benefits (Hofstetter, 1998).

12 Contextual values relate to our idea of how the world works. They reflect the influence of personal  
13 and social judgment when choosing one scientific assumption over its alternative, such as familiarity  
14 with a certain dataset or common acceptance (Hertwich et al., 2000). The following choices  
15 regarding different contextual values were considered:

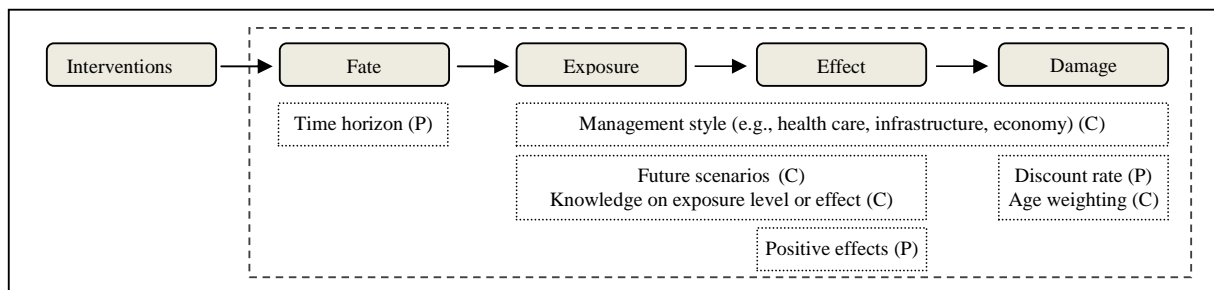
16 • Limited knowledge on causalities reflects a different level of risk that is or is not accepted by  
17 a certain perspective. According to Thompson et al. (1990) the egalitarian perspective is risk-  
18 adverse, while the individualist is risk taking. The hierarchist accepts a high level of risk, as  
19 long as the decision is made by experts (Thompson et al., 1990). Based on this consideration,  
20 the egalitarian perspective includes all known effects; the hierarchist perspective, likely  
21 effects; and for the individualist perspective, certain (proven) effects.

22 • Improved health care can reduce the DALYs attributable to a certain impact (Lorenzoni et al.,  
23 2005), while the level of legislation, education and research can increase protection and  
24 prevention. Differences in assumptions concerning the level of biological and socioeconomic



1 adaptation possibilities, which also can be defined as management style (Ezzati et al., 2004),  
 2 were considered in the definition of perspectives (Hofstetter et al., 2000). The individualist  
 3 perspective coincides with an adaptive management style, the egalitarian with a preventive  
 4 and comprehensive management style, and the hierarchist with a controlling and limited  
 5 management style (Hofstetter et al., 2000, De Schryver et al., 2009).

- 6 • Future projections on demographic developments, population displacements, changes in  
 7 gross domestic product, years of schooling and technology changes will alter the sensitivity,  
 8 size and age composition of the population and thus influence the number of incidence cases  
 9 attributable to a given emission (Mathers and Loncar, 2006). Future optimistic, baseline and  
 10 pessimistic development scenarios, as defined by Mathers and Loncar (2006), coincide  
 11 respectively with the individualist, hierarchist and egalitarian perspectives (De Schryver et  
 12 al., 2009).



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 25 Figure 1. Overview of the cause effect pathway, from intervention to damage. The calculation steps of the characterization factors are  
 26 presented in the dashed box. Choices deriving from preference values (P) and contextual values (C), considered at each calculation  
 27 step, are presented in the dotted boxes.

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 29  
 30 <heading level 2> Global damage of water consumption and outdoor emissions

31 The global damage from outdoor emissions was calculated using inventory data for the year 2000  
 32 from Sleeswijk et al. (2008). For water scarcity, country-specific water consumption data for the year  
 33 1995 were derived from the Watergap2 global model (Alcamo et al., 2003). For each impact  
 34 category, the substances contributing most to the global impact per capita (DALY/capita) were  
 35 identified and presented. A population of 5.7 billion people in 1995 and 6.1 billion people in 2000  
 36 was considered (UNDESA, 2008). To evaluate the global damage caused by water consumption and

1 outdoor emissions in the year 2000, the per capita global impact was multiplied with the 2000  
2 population. Therefore, for water scarcity, it was assumed that the water impact per capita did not  
3 change between 1995 and 2000.

Table 1. Combination of value choices deriving from preference values (P) and contextual values (C) for the CFs, expressed for three different cultural perspectives.

Impact category	Original choices <sup>a</sup>	Value choices	P/C	Individualist	Hierarchist	Egalitarian
<b>All impact categories</b>		Time horizon	P	20 years	100 years	Infinite
		Discount rate	P	5%	3%	0%
		Age weighting	P	Yes	No	No
<b>Water scarcity</b> Pfister et al. (2009)	Age weighting: yes Discount rate: 3% Regulation of flow: standard Food water requirement: 1350m <sup>3</sup> /yr.capita	Regulation of flow (management style)	C	High	Standard	Standard
		Food water requirement (management style)	C	1000m <sup>3</sup> /yr.capita (i.e., efficient management)	1350m <sup>3</sup> /yr.capita (i.e., standard management)	1350m <sup>3</sup> /yr.capita (i.e., standard management)
<b>Ozone formation</b> Van Zelm et al. (2008)	Age weighting: no Discount rate: 0% Morbidity effects: not included Positive effects from NO <sub>x</sub> are included and excluded.	Morbidity effects <sup>b</sup>	C	No	No	Yes
		Positive effects from tropospheric ozone degradation from NO <sub>x</sub>	P	Yes	No	No
<b>Particulate matter</b> Van Zelm et al. (2008)	Age weighting: no Discount rate: 0% Type of PM: primary PM <sub>10</sub> and secondary PM from SO <sub>2</sub> , NO <sub>x</sub> and NH <sub>3</sub>	Effects from primary PM <sub>10</sub> and secondary PM from SO <sub>2</sub> , NO <sub>x</sub> and NH <sub>3</sub>	C	Primary PM <sub>10</sub>	Primary PM <sub>10</sub> + Secondary PM from SO <sub>2</sub>	Primary PM <sub>10</sub> + Secondary PM from SO <sub>2</sub> , NO <sub>x</sub> and NH <sub>3</sub>
<b>Human toxicity</b> Huijbregts et al. (2005)	Age weighting: no Discount rate: 0% Bioaccumulation essential metals: yes Carcinogenicity: all substances Noncarcinogenic effects: included Time horizon: infinite	Bioaccumulation for essential metals	C	No	Yes	Yes
		Included substances on basis of carcinogenicity Noncarcinogenic effects	C	IARC classification: 1 No	IARC classification: 1, 2A, 2B Yes	All Yes
<b>Ionizing radiation</b> Frischknecht et al. (2000)	All cancer types Discount rate: 0% time horizon: individualist, 100yr; hierarchist and egalitarian, 100,000yr Age weighting: same as presented here	Cancer types <sup>c</sup>	C	Definite cancers	Definite and probable cancers	Definite, probable, possible and remainder cancers without information
<b>Ozone depletion</b> Hayashi et al. (2006)	Age weighting: no Discount rate: 0% Cataract: included Time horizon: infinite	Cataract	C	No	No	Yes
<b>Climate change</b> De Schryver et al. (2009)	Individualist: same as presented here except discount rate is 3% Hierarchist: same as presented here Egalitarian: same as presented here	Positive effects from ozone depletion	P	Yes	No	No
		Management style (Ezzati et al., 2004)	C	Adaptive management style	Controlling management style	Comprehensive management style
		Future developments (Mathers and Loncar, 2006)	C	Optimistic	Baseline	Pessimistic

Note: Detailed descriptions can be found in the appendix 1 table 1. m<sup>3</sup>/yr.capita= cubic meter per year per capita; IARC= International Agency for Research on Cancer; PM= particulate matter; PM<sub>10</sub> particulates, <10µm.

<sup>a</sup>For all impact categories, except climate change and ionizing radiation, the original method developers presented one set of CFs embedding a certain set of value choices. For ionizing radiation and climate change, the original method developers presented CFs for the individualist, hierarchist and egalitarian perspectives.

<sup>b</sup>Morbidity effects included are asthma attacks, minor restricted activity days, respiratory hospital admissions, symptom days.

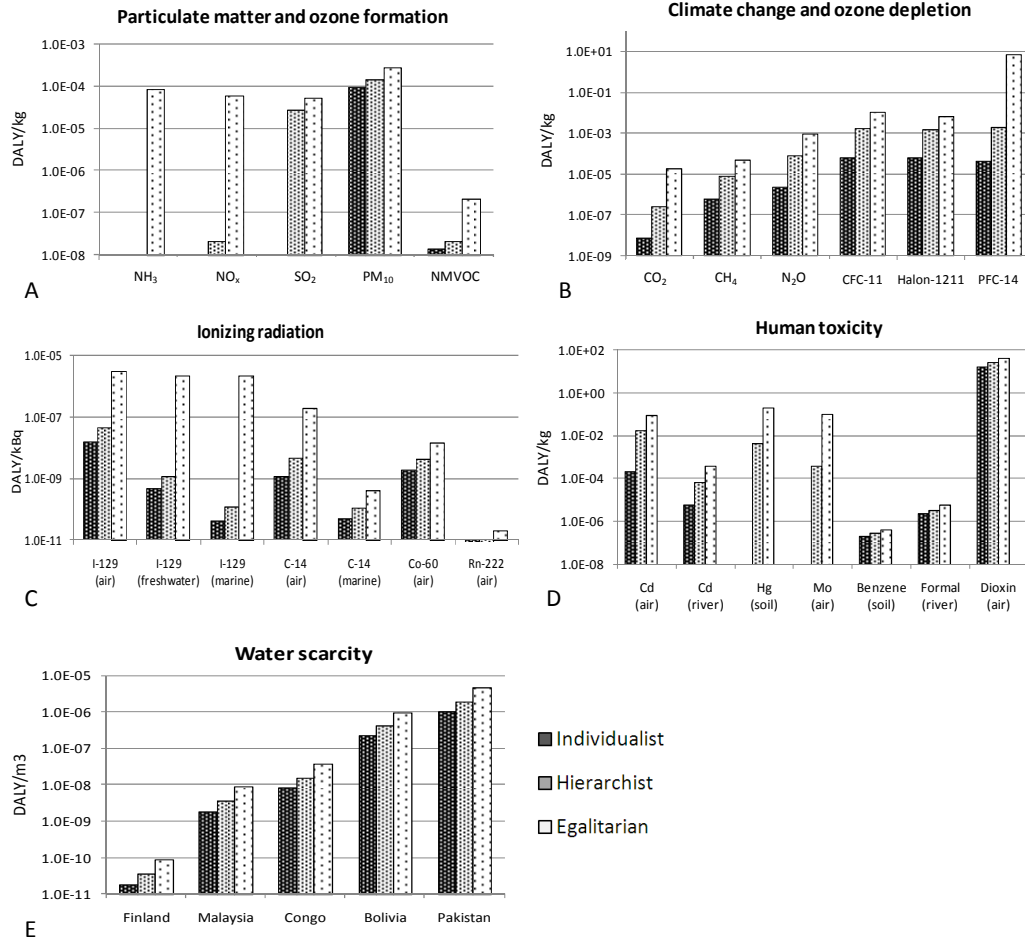
<sup>c</sup>Definite cancers are thyroid, bone marrow, lung, breast cancer; probable cancers are bladder, colon, ovary, liver, oesophagus, skin and stomach cancer; cancers without information are bone surface and all other cancers.

1 <heading 1> Results

2 Figure 2 presents the CFs for a subset of interventions (in DALY/kg, DALY/kBq or  
3 DALY/m<sup>3</sup>) for the three cultural perspectives. The full list of CFs for 1239 substances and  
4 water consumption can be found in appendix 2. The number of substances included for the  
5 impact categories particulate matter and human toxicity depends on the level of knowledge  
6 about effects or exposure assumed for each perspective. For particulate matter, effects of  
7 secondary particulates from sulphur dioxide (SO<sub>2</sub>), ammonia (NH<sub>3</sub>) and nitrogen oxides (NO<sub>x</sub>)  
8 are excluded for the individualist perspective, while effects from NH<sub>3</sub> and NO<sub>x</sub> are excluded  
9 for the hierarchist perspective. For human toxicity, the availability in knowledge about  
10 carcinogenicity and including or excluding non-carcinogenic effects results in CFs for 25  
11 substances when applying the individualist perspective, 620 substances for the hierarchist  
12 perspective, and 1002 substances for the egalitarian perspective. For the individualist  
13 perspective positive effects are included and therefore the CF of some substances turns  
14 negative, such as nitrogen oxides for ozone formation and chlorofluorocarbons and halons for  
15 climate change.

16 Table 2 lists the differences in CFs for each impact category and the relevant choices that lead  
17 to differences among perspectives. Table 2 does not cover, however, the differences in case a  
18 CF becomes zero due to specific choices concerning the certainty of effects. It also does not  
19 address the fact that for ozone formation and climate change, some CFs range from negative  
20 (i.e., reducing the impacts) to positive (i.e., causing impacts) values, depending on whether  
21 positive effects are included for the perspectives. The type of DALY refers to the combination  
22 of age weighting and discount rate, which both influence the number of DALYs calculated per  
23 case (see tables 5 and 6 in appendix 1). The difference in CFs among perspectives is the largest  
24 for substances with a relatively long residence time in the environment (> 100 years). This is

1 particularly the case for a number of emissions connected to the impact categories human  
2 toxicity (metals), ionizing radiation, ozone depletion and climate change. For example, the  
3 difference in CF between the individualist and egalitarian perspectives is five orders of  
4 magnitude for tetrafluoromethane (PFC-14; for climate change) and four orders of magnitude  
5 for iodine-129 (I-129; for ionizing radiation). For toxicity of metals, the difference in CFs  
6 among perspectives can be as much as six orders of magnitude, due to the long lifetime and  
7 inclusion or exclusion of bioaccumulation of metals. For ozone depletion, the difference in CFs  
8 among perspectives is smaller, with two to three orders of magnitude between the individualist  
9 and egalitarian perspectives. Impact categories that cover substances with a shorter residence  
10 time in the environment, i.e., ozone formation and particulate matter, show smaller differences  
11 among perspectives (up to 1.2 orders of magnitude). However, combining the effects of  
12 particulate matter and ozone formation for  $\text{NO}_x$  gives a difference of three orders of magnitude  
13 between the hierarchist and egalitarian perspectives. This is due to the exclusion of highly  
14 uncertain effects for the hierarchist perspective. For water scarcity, the CFs show relatively  
15 small differences among perspectives attributable to value choices.



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Figure 2. CFs for a range of selected substances following an individualist, hierarchist and egalitarian perspective. Graph A: combined CFs for particulate matter and ozone formation. Note that the negative CF for NO<sub>x</sub> for the individualist perspective,  $-4.2 \cdot 10^{-8}$  DALY/kg, is not presented. Graph B: combined CFs for climate change and ozone depletion. Graph C: CFs for ionizing radiation. Graph D: CFs for human toxicity. Graph E: CFs for water scarcity in different regions. Note: CFs are expressed in DALY/kg, DALY/kBq or DALY/m<sup>3</sup> using a log-scale. DALY/kg= DALY per kilogram; DALY/kBq= DALY per kilobecquerel; DALY/m<sup>3</sup>= DALY per cubic meter; NH<sub>3</sub>= ammonia; NO<sub>x</sub>= nitrogen oxides; SO<sub>2</sub>= sulphur dioxide; PM<sub>10</sub>= particulates, <10 μm; NMVOC= non-methane volatile organic compounds; CO<sub>2</sub>= carbon dioxide; CH<sub>4</sub>= methane; N<sub>2</sub>O= dinitrogen oxide; CFC-11= trichlorofluoromethane; PFC-14= tetrafluoromethane; I-129= iodine-129; C-14= carbon-14; Co-60= cobalt-60; Rn-222= radon-222; Formal= formaldehyde; Mo= molybdenum; Cd= cadmium; Hg= mercury; Dioxin= 2,3,7,8-tetrachlorodibenzo-p-dioxin.

Table 2. Difference in CFs among perspectives, per impact category (IC). For impact categories for which the time horizon is important (human toxicity, ionizing radiation, ozone depletion and climate change) a difference is made between long-lived (LL, i.e., > 100 years) and short-lived (SL, i.e., < 100 years) substances.

IC	egalitarian/ individualist	egalitarian/hierarchist	hierarchist/ individualist
Water scarcity	Max. difference is a factor of 18	Max. difference is a factor of 2.3	Max. difference is a factor of 8
	The regulation of flow is the most important choice, followed by the choice in type of DALY and water requirement	The choice in type of DALY is the only choice responsible for the difference	The regulation of flow, the choice in type of DALY and water requirement are all equally important
Ozone formation <sup>a</sup>	Max. difference is a factor of 15	Max. difference is a factor of 10	Max. difference is a factor of 1.5
	The choice in including effects with low amount of knowledge is 1.8x more important than the choice in type of DALY	The choice in including effects with low amount of knowledge is 2.5x more important than the choice in type of DALY	The choice in type of DALY is the only choice responsible for the difference
Particulate matter	Max. difference is a factor of 2.8	Max. difference is a factor of 1.9	Max. difference is a factor of 1.5
	The choice in type of DALY is the only choice responsible for the difference	The choice in type of DALY is the only choice responsible for the difference	The choice in type of DALY is the only choice responsible for the difference
Human toxicity <sup>a</sup>	Metals: max. 6 orders of magnitude Non metals: max. factor of 10	Metals: max. 4 orders of magnitude Non metals: max. factor of 22	Metals: max. 5 orders of magnitude Non metals: max. factor of 7
	Metals: the choice in time horizon and bioaccumulation determines the difference in perspective Non metals: the choice in including noncarcinogenic effects is 2x more important than the choice in type of DALY	Metals: the choice in time horizon determines the difference in perspective Non metals: the choice in including carcinogenic effects (IARC classification) is 12x more important than the choice in type of DALY	Metals: the choice in time horizon and bioaccumulation mainly determines the difference in perspective Non metals: the choice in including noncarcinogenic effects is 2x more important than the choice in type of DALY
Ionizing radiation	LL: max. 4.4 orders of magnitude SL: max. factor of 11	LL: max. 4 orders of magnitude SL: max. factor of 2.2	LL: max factor of 11 SL: max factor of 5.2
	LL: the choice in time horizon is more than 2000x more important than the choice in type of DALY or the knowledge about effects SL: the choice in type of DALY, the knowledge about effects and time horizon all contribute with the same importance to the difference between scenarios	LL: the choice in time horizon is more than 2000x more important than the choice in type of DALY or the knowledge about effects SL: the choice in type of DALY, the knowledge about effects and time horizon all contribute with the same importance to the difference between scenarios	LL: the choice in time horizon is 2x more important than the choice in type of DALY or the knowledge about effects SL: the choice in type of DALY, the knowledge about effects and time horizon all contribute with the same importance to the difference between scenarios
Ozone depletion	LL: max. 2.5 orders of magnitude SL: max. factor of 30	LL: max. 1.5 orders of magnitude SL: max. factor of 20	LL: max. factor of 9 SL: max. factor of 6
	LL: choice in time horizon can rise up to 60x more important than choice in type of DALY and up to 7x than the inclusion of cataract SL: the choice in including cataract is 8x more important and twice as important than choice in type of DALY and time horizon	LL: the choice in time horizon and including cataract are main important for the difference in scenario, being respectively 15x and 11x more important than the choice in type of DALY SL: the choice in including cataract is 9x and 11x more important than the choice in time horizon and type of DALY	LL: the choice in time horizon is 4 to 5x more important than the type of DALY or including cataract SL: the choice in time horizon is up to 2x more important than the type of DALY or including cataract
Climate change <sup>b</sup>	LL: max. 5 orders of magnitude SL: max. 2.5 orders of magnitude	LL: max. 3 orders of magnitude SL: max. factor of 10	LL: max. 2 orders of magnitude SL: max. 1.5 orders of magnitude
	LL: the choice in time horizon is max. 400x more important than choice in management style and future scenarios, that on its turn is 4x more important than the	LL: the choice in time horizon is max. 300x more important than choice in type of DALY or future scenarios and management style	Independent of the lifetime of the substance, the choice in time horizon is equally important than the choice in management style and future scenarios; The choice in

	choice in type of DALY SL: the choice in management style and future scenarios is 4x more important than choice in type of DALY, and 1.3x more important than the choice in time horizon	SL: the choice in time horizon, management style, future scenarios and type of DALY is equally important	DALY is less important
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Note: The numerical values represent the maximum ratios of the egalitarian/individualist, egalitarian/hierarchist and hierarchist/individualist scenarios. The type of DALY refers to the combined choice in age weighting and discount rate.

<sup>a</sup>Only the max. differences for substances included in both perspectives are presented. For the egalitarian/individualist perspective vinylchloride shows a maximum difference of a factor of ten. For the egalitarian/hierarchist scenario the same substance shows a max. difference of a factor of 1.5.

<sup>b</sup>Both positive and negative CFs are reported (see appendix 2). Only positive CFs are considered in the ratio calculations. The negative and zero values are further discussed in the text.



1 The global human damage (temporal cumulated) caused by water consumption and outdoor  
 2 emissions in the year 2000 is 4 million DALYs for the individualist, 21 million DALYs for  
 3 the hierarchist perspective, and 570 million DALYs for the egalitarian perspective (table 3).  
 4 This implies that the loss in (disability adjusted) life years caused by one average world  
 5 citizen due to water consumption and emissions in the year 2000 is between 0.2 and 34 days,  
 6 depending on the perspective considered.

7 Table 3. Interventions responsible for 95% of the global human damage caused by water consumption and outdoor emissions in the year  
 8 2000. The damage scores (in DALY/capita) and percentage damage contribution (in %) are presented.

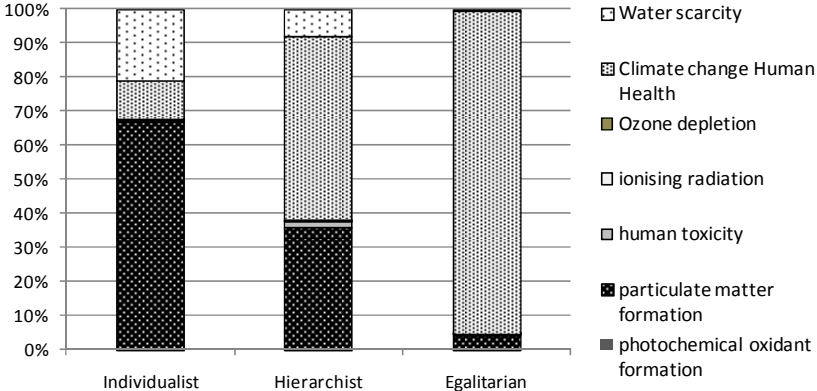
Substance/source	Compartment of emission	Individualist		Hierarchist		Egalitarian		Driving choices
		DALY/ (capita.yr)	%	DALY/ (capita.yr)	%	DALY/ (capita.yr)	%	
Water consumed		1.4E-4	21.1%	2.8E-4	8.3%	6.7E-4	0.7%	Management style (regulation of flow) + type of DALY
Particulates, < 10 µm	Air	4.4E-4	66.9%	6.5E-4	19.1%	1.2E-3	1.3%	Type of DALY
Carbon dioxide, fossil	Air	3.5E-5	5.3%	1.2E-3	35.2%	8.2E-2	87.8%	Time horizon
Methane <sup>a</sup>	Air	3.0E-5	4.6%	3.6E-4	10.7%	2.5E-3	2.6%	Management style-future scenarios
Sulfur dioxide	Air	2.4E-8	0.0%	5.7E-4	16.8%	1.1E-3	1.2%	Type of effects included
Dinitrogen monoxide	Air	4.4E-6	0.7%	1.6E-4	4.6%	1.8E-3	1.9%	Management style-future scenarios + time horizon
CFC-12	Air	9.9E-7	0.2%	5.7E-5	1.7%	5.6E-4	0.6%	Management style-future scenarios + time horizon
Others		7.8E-6	1.2%	1.2E-4	3.6%	3.6E-3	3.8%	
Total damage (in DALY/capita)		6.5E-4	100%	3.4E-3	100%	9.3E-2	100%	
Total damage (in disability-adjusted life days/capita)		0.2		1.2		34		
Total global damage for the world (in DALY), using a population of 6.12 billion people		4.0E+6		2.1E+7		5.7E+8		

9 Note: The column "driving choices" presents the value choices responsible for the difference among perspectives. The type of DALY refers  
 10 to the choice in age weighting and discount rate.

11 <sup>a</sup>Sum of methane from biogenic and fossil origin. No degradation products are included in the inventory dataset or CFs, therefore there is an  
 12 underestimation of the damage from methane (more details can be found in the appendix 1).  
 13  
 14

15 Figure 3 illustrates the share of each impact category to the global human health damage (in  
 16 %) caused by water consumption and outdoor emissions in the year 2000, for the three  
 17 perspectives. Depending on the perspective, the damage is driven mainly by three impact  
 18 categories: water scarcity, particulate matter and climate change. All other impact categories

1 contribute less than 2% to the damage. Of the total damage score of the individualist  
 2 perspective, 67% is attributable to particulate matter formation and 21% to water scarcity. For  
 3 the egalitarian perspective, 95% of the total damage score is related to climate change (mainly  
 4 CO<sub>2</sub> emissions). For the hierarchist perspective, the total damage score is distributed almost  
 5 equally between climate change ( $\pm 50\%$ ) and particulate matter ( $\pm 40\%$ ), together with a  $\pm 10\%$   
 6 contribution by the impact of water scarcity. Independent of perspective, six substances and  
 7 water consumption are responsible for more than 95% of the total damage (see table 3).  
 8 Substance contributions per impact category can be found in the appendix 1 (table 4).



9  
 10 Figure 3. Global human health damage (share of each impact category, expressed in %) caused by outdoor emissions and water  
 11 consumption in the year 2000, following the individualist, hierarchist and egalitarian perspectives.

12  
 13

1 <heading 1> Discussion

2 In this paper, existing models to calculate CFs for water consumption and 1239 substances  
3 (Pfister et al., 2009, Van Zelm et al., 2008, Huijbregts et al., 2005, Frischknecht et al., 2000,  
4 Hayashi et al., 2006, De Schryver et al., 2009) were adapted following the Cultural Theory,  
5 using different value choices for individualist, hierarchist and egalitarian perspectives (e.g.,  
6 Schwarz and Thompson, 1990, van Asselt and Rotmans, 1996, Hofstetter, 1998, Hertwich et  
7 al., 2000, Hofstetter et al., 2000, Steen, 2006). This application allows for a transparent way  
8 of handling value choices for environmental assessments and decision making. While we  
9 illustrate this work by focusing on damage to human health, the technique can also be applied  
10 to assess impacts from other damage categories such as, ecosystem quality and resource  
11 depletion.

12 The calculations show that scenario-specific differences in CFs depend on the persistence of  
13 the substance in the environment. For persistent substances, such as long-lived greenhouse  
14 gases or metals, the difference in CFs can reach up to six orders of magnitude. The chosen  
15 time horizon used for the fate and exposure factor is mainly responsible for this difference  
16 (preference value). This also implies that for CFs on midpoint level (e.g., global warming  
17 potentials) the applied time horizon is an important value choice. For short-lived substances,  
18 the difference in CFs among perspectives mainly derives from choices regarding the effect  
19 and damage factor, namely the exposure or effects included based on the amount of  
20 knowledge (contextual value) and the choice in type of DALY (preference value). For water  
21 scarcity, the difference among perspectives is driven mainly by the management style that  
22 decides on how the water flow is regulated (contextual value).

23

24 <heading 2> Limitations in defined choices

1 Despite the substantial effort to create a coherent implementation of all value choices  
2 identified in the models employed, it was not possible to include all choices in the calculation  
3 of the CFs.

4 First, due to data limitations, perspectives on future scenarios (e.g., migration patterns and  
5 gross domestic product projections) and management style (socioeconomic adaptations) were  
6 not included, except for climate change. For climate change, the choices for future scenarios  
7 and socioeconomic adaptation made the CFs from the egalitarian and individualist  
8 perspectives differentiate by one order of magnitude. An improved health care system, better  
9 education or research can lower the damage factors, while demographic changes can influence  
10 the number of cases affected. The inclusion of future scenarios and management style can be  
11 an important contributor to the difference among perspectives for substances with long  
12 response times, such as a number of ozone-depleting chemicals. Further research on including  
13 future scenarios for all impact categories is therefore needed.

14 For ionizing radiation, limited data sources constrained the available exposure factors at the  
15 corresponding time horizon (see appendix 2). In total, CFs were derived for 52 ionizing  
16 substances. For the hierarchist perspective, CFs for three substances are missing (Pu-238 and  
17 Ra-226 emitted to air; Ra-229 emitted to freshwater) and for the individualist perspective,  
18 CFs for four substances are missing (Pu-238, Pb-210 and Ra-226 emitted to air; Ra-229  
19 emitted to freshwater). This lack of CFs can lead to an underestimate of the damage score for  
20 the individualist and hierarchist perspectives when analyzing emission data that cover these  
21 substances (such as nuclear waste and electricity from nuclear and coal power plants). Note  
22 that for the global damage calculations, the missing substances were not present in the  
23 inventory dataset and thus no underestimation attributable to the lacking CFs arises.

24 Information on cause-effect relationships was not always available and therefore not all health  
25 effects could be included in the different scenarios (see appendix 1, table 1). Examples are

1 diarrhea incidence from water scarcity (Banda et al., 2007), premature deaths from particulate  
2 matter (Reiss et al., 2007), solar keratosis from ozone depletion (Lucas et al., 2008) and  
3 dengue and tick-borne encephalitis from climate change (Haines et al., 2006). This omission  
4 results in an underestimation of CFs, particularly for the egalitarian perspective, as this  
5 perspective considers all possible effects, including those with limited knowledge.

## 6 7 <heading 2> Subjective assumptions

8 The ultimate goal for developing different scenarios is to provide tools to evaluate possible  
9 outcomes. Exploring various trajectories and considering alternative plausible states of the  
10 world widens stakeholder's or decision maker's perspective and highlights issues that  
11 otherwise would be missed (Mahmoud et al., 2009). In this study, we applied the Cultural  
12 Theory for exploring plausible states of the world (Thompson et al., 1990). However,  
13 subjective assumptions were inevitable in the construction of the scenarios:

- 14 • To account for different temporal visions of life and society, various time horizons  
15 were considered for the fate and exposure factor, while the damage factors included  
16 specific discount rates. The egalitarian perspective considers no discount rate, which is  
17 consistent with an infinite time horizon. A 5% discount rate for the individualist  
18 perspective results in a maximum of 20 life years lost at birth, and the same maximum  
19 DALYs result when applying a 20-year time horizon. A 3% discount rate for the  
20 hierarchist perspective results in a maximum of 30 life years lost at birth, which is  
21 lower than the maximum DALY obtained when applying a 100-year time horizon. In  
22 general, applying a 5% or 3% discount rate for the individualist or hierarchist  
23 perspectives respectively gives a lower damage factor than applying a time horizon of  
24 20 or 100 years for the damage factor. The combined use of time horizon and discount  
25 rate is common practice in life cycle assessment (e.g., Hauschild and Potting, 2005,

1 Jolliet et al., 2003). Consistently applying a time horizon or a discount rate throughout  
2 the calculation steps of CFs is recommendable and warrants further research.

3 • Which time horizon or discount method to select is difficult to underpin. Other time  
4 horizons or discount methods than those applied here could be selected. For example,  
5 for the egalitarian perspective one can argue that an infinite time horizon is unrealistic  
6 for some emissions (residence time of > 100,000 years) and a more appropriate time  
7 horizon could be selected, such as a 500-year time frame (IPCC, 2000). Furthermore,  
8 instead of a constant discount rate a non-linear discount rate could be applied, as  
9 suggested by Harvey (1994).

10 • In this paper only the effects of equal weights and unequal weights as provided by the  
11 WHO are assessed by age weighting (WHO, 2008). However, not all studies agree in  
12 assigning different weights to a year of life lost at different ages, nor in the relative  
13 magnitude of the weights (Lopez et al., 2006).

14 • Positive effects, such as from NO<sub>x</sub> emissions regarding tropospheric ozone  
15 degradation, were only included for the individualist perspective following their  
16 positive attitude towards environmental benefits (van Asselt and Rotmans, 1996).  
17 However, in most cases positive effects are also uncertain. This is contradicting with  
18 the individualist perspective which only includes proven effects (Thompson et al.,  
19 1990). The high level of uncertainty argues for excluding positive effects for the  
20 individualist and hierarchist perspectives and including them for the egalitarian  
21 perspective. Here, positive effects are essentially assessed on basis of their positive  
22 environmental impacts and not their level of uncertainty.

23 • Causalities with limited knowledge are manifold, such as uncertainty in morbidity  
24 effects from ozone formation, and the effects from secondary aerosols. Effects or  
25 substances with limited scientific proof are excluded from the individualist perspective,

1 while included for the egalitarian perspective. However, for the hierarchist perspective,  
2 the required level of knowledge is more difficult to define. For instance, some  
3 researchers (Gloria et al., 2006, Ligthart, 2004) argue that the fate and exposure models  
4 used to address the human toxicity of metals, such as USES-LCA (Uniform System for  
5 the Evaluation of Substances; Van Zelm et al., 2009), are highly uncertain. Therefore,  
6 bioaccumulation of essential metals (i.e., cobalt, copper, manganese, molybdenum and  
7 zinc) is expected to be overestimated. Excluding bioaccumulation in the hierarchist  
8 perspective would decrease CFs for essential metals up to four orders of magnitude.

9 The Cultural Theory is recognized as not being able to account for the full variety of world  
10 visions and perspectives (conform van Asselt and Rotmans, 1996) and is sometimes criticized  
11 because it lacks full empirical validation (Marris et al., 1998, O’Riordan and Jordan, 1999,  
12 Steg and Sievers, 2000). We are aware that more research is needed to analyze how these  
13 perspectives are linked to realistic human actor groups (e.g., building further on Tukker et al.,  
14 2000). Using surveys would be another way of deriving at scenarios in life cycle impact  
15 assessment. Therefore, the constructed scenarios can be seen as default scenarios and  
16 depending on the questions to be answered, we recommend the development of a flexible  
17 system that allows users to adapt and construct their own scenarios.

## 18 19 <heading 2> Global damage of water consumption and outdoor emissions

20 Depending on the perspective chosen, the global damage caused by water consumption and  
21 outdoor emissions in the year 2000 is mainly caused by the impacts from climate change or  
22 particulate matter. The global human damage (temporal cumulated) caused by water  
23 consumption and outdoor emissions in the year 2000 (in DALY/capita) is for the individualist  
24 perspective two orders of magnitude lower than for the egalitarian perspective and derives  
25 mainly from the difference in time horizon chosen for climate change. The chosen time  
26 horizon determines how much damage caused by persistent substances, in this case carbon

1 dioxide, is included in the damage score. For climate change, taking only part of the damage  
2 into account causes a difference of three orders of magnitude between the egalitarian and  
3 individualist perspectives. This makes the time horizon the most important value choice for  
4 the difference in global damage among perspectives. The damage from particulate matter  
5 dominates the global damage outcome for the individualist perspective. As a matter of  
6 comparison, our results for particulate matter represent approximately half (for individualist)  
7 to approximately the same (for egalitarian) burden of disease from outdoor air pollution in the  
8 year 2000 calculated by Cohen et al. (2005).

9 The global damage calculations have several limitations:

- 10 • Not all human health impacts were considered in this assessment, mainly due to lack  
11 of data. Impacts, such as from noise and indoor air emissions, should be included in  
12 order to improve the calculation of the global damage;
- 13 • Except for water scarcity, all impacts are calculated by combining global total  
14 emission data with average CFs. Further research is needed to evaluate both the  
15 inventory and the CFs of impacts at regional and local levels (e.g., urban versus rural  
16 versus remote emissions). Within this study, regionalization is especially required for  
17 ozone formation and particulate matter;
- 18 • For particulate matter, the CF of  $PM_{10}$  (from Van Zelm et al., 2008) is used to  
19 calculate the global damage from global  $PM_{10}$  emissions (from Sleeswijk et al. 2008).  
20 Because  $PM_{10}$  is an important contributor to the total damage, better assessment of the  
21 size distribution below  $PM_{10}$ , i.e.  $PM_{2.5}$  and  $PM_{0.1}$ , would be necessary to reduce  
22 uncertainty in the results (Dockery et al., 1993);
- 23 • We considered total water consumption (industry, households and irrigation) to  
24 evaluate the damage from water scarcity. The result is the potential number of



1 DALYs/yr that can be avoided if all water consumed today was saved under current  
2 water scarcity conditions. It is however virtually impossible to save all water used for  
3 irrigation. This implies that the global damage from water consumption is probably  
4 overestimated in our current calculations, particularly because water from irrigation  
5 accounts for 85% of the global water consumption (Shiklomanov, 1999);

- 6 • To evaluate the damage caused by water consumption in 2000, water consumption per  
7 capita for 1995 is multiplied with the population in 2000. Therefore, pressure per  
8 capita is assumed not to change between 1995 and 2000, which is a source of  
9 uncertainty that needs further refinement.

10

## 11 <heading 1> Conclusion

12 Value choices in impact assessment modeling were implemented by applying the Cultural  
13 Theory. CFs for 1239 substances and water consumption are provided, covering the human  
14 health impact categories of water scarcity, ozone formation, particulate matter, human  
15 toxicity, ionizing radiation, ozone depletion and climate change. Depending on the chosen  
16 perspective, CFs can range from negative to positive values and differ up to six orders of  
17 magnitude. The most important value choice for substances with a relative long life time is  
18 the choice in time horizon (fate factor), followed by the effects included and the choice in age  
19 weighting and discount rate of the DALY calculation (damage factor). For substances with a  
20 relative short life time, the most important choices are the effects included and choice in age  
21 weighting and discount rate.

22 When applying the three sets of CFs to assess the global emissions and water consumption,  
23 the damage to human health differs by 2 orders of magnitude among the chosen perspectives  
24 and is mainly driven by the time horizon chosen for climate change. The global impact comes  
25 mainly from particulate matter when considering an individualist perspective, climate change

1 when considering an egalitarian perspective, and particulate matter and climate change when  
2 considering a hierarchist perspective. Water scarcity should also not be neglected, as it  
3 contributes considerably to the global impact for the individualist and hierarchist perspectives.

4 All other impact categories contribute less than 2% to the total global damage.

5 The results of this study clearly indicate that value choices within impact assessment  
6 modeling influence the absolute values of CFs and the overall damage calculation. Further  
7 research is required to evaluate whether cultural perspectives can also change the ranking  
8 among products and services, and conclusions of life cycle assessment studies.

9

## 10 <heading level 1> Acknowledgements

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17

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