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Consumption-as-usual instead of ceteris paribus assumption for demand

Integration of potential rebound effects into LCA

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Abstract
Background, aims, and scope Life cycle assessment (LCA) according to ISO 14040 standard (ISO-LCA) is applied to assess the environmental impact per functional unit of new or modified products. However, new or modified products can also induce demand changes—so-called rebound effects. If overall environmental impact is of interest, there is a need to assess the potential magnitude of such rebound effects and to allow recommendations on how to mitigate these effects. To do so, this study proposes to complement the constant demand assumption (implicitly assumed by the ISO-LCA), commonly known as the ceteris paribus assumption, with a consumption-as-usual assumption allowing a systematic stepwise inclusion of rebound effects.
Materials and methods We base our results on a formal description of household consumption. To indicate the relevance of the proposed integration of rebound effects, different comparative LCAs are reviewed and the concept is applied to mobility as illustrative examples.
Results Based on a description of household demand and consumption feedback loops, we propose the consumption-as-usual concept, which in contrast to the constant demand assumption assumes that (1) the use of household resources for consumption does not change and (2) preferences remain the same. Household resources for example are purchasing power (we assume that households do not work less), time, and living space. We outline how this concept allows integrating potential rebound effects into ISO-LCA by considering three different cases of reallocating freed household resources. To illustrate the use of the consumption-as-usual concept, we draw implications for different comparative LCAs from the literature and illustrate cases with income and time rebound for different personal travel modes.
Discussion The consumption-as-usual concept is applicable to a broad range of product modifications and allows an important complementation of the LCA regarding rebound effects. For products with various changes in the need for household resources, the assessment becomes however a challenging task. The limits of the consumption-as-usual concept are mainly given by its two underlying assumptions. Therefore, new or modified products with the potential to change consumer preferences or even the amount of household resources used for consumption go beyond this concept.
Conclusions The integration of rebound effects is feasible for many comparative LCAs. It helps in increasing the reliability of the assessment of overall environmental impact reduction through new or modified products. In addition, a basis is provided with which to mitigate rebound effects and give appropriate recommendations to product users.
Recommendations and perspectives Potential rebound effects should be included in LCA in order to guide consumers and policy towards sustainable consumption. We recommend the consumption-as-usual concept for this purpose. To predict rebound effects under consumption as usual instead of outlining potential amplitudes, further research on household preferences is needed and an optimisation model should be applied for household consumption. However, even if data are available for such a prediction, the assessment of potential rebound effects is

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still recommended in order to recognise dangers and opportunities in consumption changes.

Keywords Feedback loops · Household consumption · ISO-LCA

1 Background, aim, and scope

Life cycle assessment (LCA) provides a powerful tool for the assessment of the environmental impact of products[1] and therewith allows for their improvement. By comparing the environmental impact of different options in reference to the same functional unit, defined as the quantified performance of a product system (ISO 2006), the ISO-LCA implicitly assumes constant demand for consumption. A change from product system (A) to product system (B) delivering the same functional unit is assumed not to change the consumption. However, new or modified products can also induce demand changes—so-called rebound effects. For instance, various studies have shown that households increase consumption subsequent to increasing energy efficiency because of decreasing price of energy services (e.g. Brannlund et al. 2007; Sorrell 2007). But beside changes in price, changes in time use (speed) or other 'consumption costs' changed simultaneously with the greater energy efficiency, which can also influence demand. If the goal of the LCA is to assess the reduction of overall environmental impact, the feedback loops through changing consumption induced by changing consumption costs should be considered.

Different approaches have been proposed in the literature to include such rebound effects in LCA. Most efforts have been devoted to income rebound (e.g. Hertwich 2005), which Thiesen et al. (2008) propose to include in LCA by considering changes in price differences. In different comparative LCAs, not only time rebound (Spielmann et al. 2008) but also rebound effect due to changes in volume (Hofstetter et al. 2006) is considered. However, these approaches differ in their assumptions on how the rebound is integrated, and no general proposal exists to handle different possible rebound effects for the interpretation of ISO-LCA. Accordingly, the co-ordination action for innovation in life cycle analysis for sustainability concludes that 'although there is a number of LCA studies that have incorporated rebound mechanisms, no generally applicable rules have been developed to do so' (Heijungs et al. 2009).

[1] The term 'product' as used in this article includes all economic output purchased by households (i.e. also services).

The purpose of this paper was to formulate a method which allows for a systematic, stepwise integration of potential rebound effects into ISO-LCA.

2 Rebound effects from product change

2.1 Household consumption and feedback loops

Simplified and in line with classical economics, we assume that manufacturers try to maximise their output, $Q(C, L, N)$, which is limited by capital C, the labour L, and inputs from nature N. We focus in this article on the demand side, where households try to maximise their utility U by the consumption of a certain amount, $x(i, t)$, of all possible products, $i=1,...,I$, at the time t (Fig. 1). Household consumption is constrained by the different types of household resources, $j=1,...,J$ and the total amount of this resource, $A_{res}(\text{tot}, j, t)$. These include income and time (Becker 1976). But also other factors, like storage volume, skills, or saturation could constrain consumption (Hofstetter et al. 2006). Thus, the utility maximisation becomes an optimisation problem. If new or modified products change the use of these household resources, households will adapt their consumption by reallocating the different household resources. Monetary flows come from manufacturer through labour market to the household and through consumption go back to the manufacturer. In the other direction, households provide manufacturers with labour and manufacturers deliver different goods. This manufacturer–household exchange leads to environmental impact and degradation through the consumption and production of goods.

If a manufacturer now changes the environmental impact of a product i in a first time span, $\tau_1 = [t_0, t_1]$, the impact change solely depends on the change in the environmental impact per functional unit, $\Delta Y_{env}(i, \tau_1) = Y_{env}(i, t_1) - Y_{env}(i, t_0)$. However, if with the same product modification the use of household resources per functional unit, $\Delta Y_{res} = Y_{res}(j, i, t_1) - Y_{res}(j, i, t_0)$, also change, a consumption feedback loop is induced in a second time span ($\tau_2 = [t_1, t_2]$), first, giving the household new 'space' for consumption; second, by leading to a reallocation of consumption; and finally, to a change in the environmental impact.

For the reallocation of household resources, the preferences of households are decisive and can be estimated by different complementing concepts: For perfect data availability, demand change can be estimated by applying own and cross consumption costs (analogue to price) elasticity of demand, $\eta(i,j)$. Relating to the mental budgets as proposed by Thaler (1999) constant household resource budgets can be assumed. According to this approach,

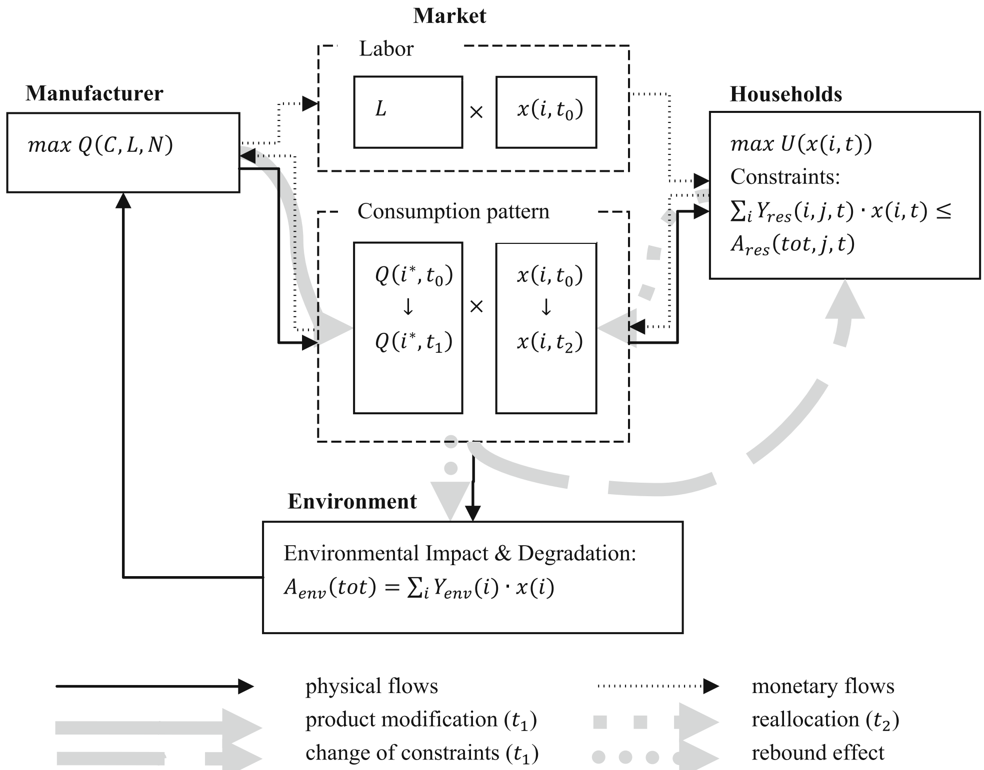

Fig. 1 Interaction of manufacturer and household including environmental impact and consumption feedback loops induced by product modification (description cf. Section 2.1 and Table 1). If the manufacturer modifies the product i^* and reduces the environmental impact per functional unit $Y_{env}(i^*)$, the overall environmental impact reduces by $\Delta A_{env}(\tau_1) = \left[Y_{env}\left(i^*,t_1\right) - Y_{env}\left(i^*,t_0\right)\right] \cdot x\left(i^*,t_0\right)$ (primary feedback loop). However, if the product changes also the use of household resources $Y_{res}(i^*, j)$, household resources are freed and a reallocation of the consumption allows to increase the utility within the same constraints $A_{res}(\text{tot}, j)$. This secondary feedback loop from consumption can lead to a rebound effect

households use the same share of household resources, $S(i,j)$ (with $\sum_i S(i,j) = 1$), for different products which represent different purposes. The marginal consumption concept is close to that of constant budgets. However, the changing preferences that accompany an increase in size of household resources are considered. Most prominently, the share used for food decreases with increasing income (e.g. Banks et al. 1997). But, as with income, it could be shown that average consumption is close to marginal consumption for smaller time steps (Stock 1988).

2.2 Feedback loops and rebound effects

The rebound effect originally described the relation between increased energy efficiency and increasing energy consumption due to lower price (Brookes 2000). However, in LCA the rebound effect is used in a broader sense that includes product aspects resulting in changes in behaviour subsequent not only to a reduction in energy use but also to a reduction of product's environmental impact (e.g. Spielmann et al. 2008; Thiesen et al. 2008; Hofstetter et al. 2006). In line with the use of the term in this journal, rebound effect can be described by the consumption feedback loops of product modification (see above). This refers also to the feedback loops observed in the human–environmental system inter-relations (Scholz 2011). The definition of the rebound effect, RE_{i^*}, induced by the modification or replacement of product i^* can be expressed as

$$\text{RE}_{i^*} = 1 - \Delta A_{env}(\text{tot}, \tau_2)/\Delta A_{env}(i^*, \tau_1) \tag{1}$$

where the denominator is the reduction of environmental impact assuming constant demand, $\Delta A_{env}(i^*, \tau_1)$, and the numerator is the actual overall (total) reduction of environmental impact, $\Delta A_{env}(\text{tot}, \tau_2)$, with tot denoting the set of all consumed products ($\text{tot} = \cup_i\{i\}$). The change in environmental impact, ΔA_{env}, can be described as a function of the consumption x in functional units and the energy efficiency (or environmental impact per functional unit), Y_{env}:

$$\Delta A_{env}(i^*, \tau_1) = x\left(i^*, t_0\right) \cdot \Delta Y_{env}\left(i^*, \tau_1\right) \tag{2}$$

$$\Delta A_{env}(\text{tot}, \tau_2) = x\left(i^*, t_2\right) \cdot \Delta Y_{env}\left(i^*, \tau_1\right) + \sum_{i \neq i^*} \Delta x(i, \tau_2) \cdot Y_{env}(i) \tag{3}$$

Hence, to determine the rebound, the new amount of consumption for the different products x needs to be known. Comparative LCA implicitly assumes no change in consumption, $x(i, t_0)=x(i, t_1)=x(i, t_2)$, and applying this assumption in Eqs. 1–3 above leads to rebound equal to zero.

However, this neglects consumption feedback loop. Therefore, the concept of consumption-as-usual is introduced.

3 Integration of rebound effects into LCA

3.1 The consumption-as-usual concept

The consumption-as-usual concept aims at a more reliable description of how the consumer can be expected to react to changing consumption costs. Thus, the concept of consumption as usual, similarly to business-as-usual, relies on observations made in the past. The following two basic assumptions underlie the consumption-as-usual concept (Table 1):

1. Assumption: The total of household resources used for consumption does not change subsequent to product modification ($A_{res}(\text{tot}, j, t_0)=A_{res}(\text{tot}, j, t_2)$).
2. Assumption: The preference for allocations of household resources to different purposes does not change subsequent to product modification.

These assumptions can be seen as a ceteris paribus for household consumption behaviour, which however does not signify ceteris paribus for demand if the new or modified product changes the need for consumption constraining household resources. The first assumption implies that freed household resources are reallocated for consumption. The second assumption states how these freed resources are reallocated. These two assumptions allow the determination of the new consumption, $x(i, t_2)$, and thus determine the rebound (Eqs. 1 to 3). Often, there are considerable uncertainties in the descriptions of the preferences. To maintain high transparency, we propose the assessment of three simple cases, which outline possible reallocations of the freed households resources $(x(i^*, t_0)\cdot \Delta Y_{res}(j, i^*, \tau_1))$:

More of the same: (4)

$$x\left(i^*, t_2\right) = x\left(i^*, t_0\right)\cdot\left[1 + \left[\Delta Y_{res}\left(j, i^*, \tau_1\right)/Y_{res}\left(j, i^*, t_1\right)\right]\right]$$

More of similar: (5)

$$x(i, t_2) = x(i, t_0)\cdot\left[1 + \left[x\left(i^*, t_0\right)\cdot \Delta Y_{res}\left(j, i^*, \tau_1\right)\cdot S_s(j, i)\right]/Y_{res}(j, i, t_1)\right]$$

More of other: (6)

$$x(i, t_2) = x(i, t_0)\cdot\left[1 + \left[x\left(i^*, t_0\right)\cdot \Delta Y_{res}\left(j, i^*, \tau_1\right)\cdot S(j, i)\right]/Y_{res}(j, i, t_1)\right]$$

In the *more of the same* case, the freed household resources are used for the modified or new product. If for instance time use per kilometre would be reduced by 30%, consumption (e.g. kilometres) would increase by 43% and

Table 1 Description of variables for the consumption-as-usual concept

Variable	Description
i	Consumption category (i=1,..., I), with i^* for modified product
t_0, t_1	Time before (t_0) and after product modification (t_1)
t_2	Time after reallocation of household resources
τ_1, τ_2	First time span (t_0, t_1); second time span (t_1, t_2)
j	Type of hh resource (e.g. income, time)
Q	Economic output
C	Capital
N	Natural resources
L	Labour
U	Utility
$Q(i, t)$	Product (or consumption category)
$x(i, t)$	Amount of consumption in functional unit [e.g. kg, pkm, etc.]
$A_{res}(i, j, t)$	Amount of used hh resources [€, h, m^3 …]
$A_{env}(i, t)$	Amount of environmental impact [e.g. CO_2-eq., EIP, etc.]
$S(i, j)$	Share of hh resource used for products, i [%]
$S_s(i, j)$	Share of hh resource used for products, i, similar to product, i^* [%]
$Y_{res}(i, j, t)$	hh resource intensity (A_{res}/x)
$Y_{env}(i, t)$	Energy, environmental intensity (A_{env}/x)
$Y_{env/res}(i, j, t)$	Environmental impact per household resource (A_{env}/A_{res})
RE(i^*)	Rebound effect of modification of product, i^* [%]
$\eta(i, j)$	Elasticity of consumption and hh resource [%]

hh household, *EIP* ecoindicator points (Eco-Indicator 99) therewith total time use would remain the same. For the *more of similar* case, freed household resources are used for products fulfilling the same purpose (e.g. different travel modes), by assuming the same share of household resource, $S_s(j, i)$ for the reallocation. The *more of other* case uses, instead of the share for similar consumption categories, the share from the total consumption, $S(j, i)$.

These three cases do not consider the rebalancing of household resources. For instance, if the price of car driving decreases, according to the first case, the driven kilometres increase, and thereby more time is used, which has to be rebalanced according to assumption 1. For the integration of rebound effects into LCA, we therefore propose additionally assessing the costs of the rebound effects in terms of other household resources. To predict the consumption-as-usual reaction and therewith rebound effect, an optimisation model should be applied that considers the different household resources. However, the focus on the three cases described above is more salient and permits recommendations for product users as to how freed household resources are best used.

3.2 Method to integrate rebound effects into comparative ISO-LCA study

Based on the introduced consumption-as-usual concept, we outline how rebound effects could be integrated into ISO-LCA. In this, we follow the major LCA steps.

Goal and scope definition If the goal of the LCA is to determine the change in overall environmental impact due to the modification of a final demand product, consumption as usual is the most meaningful assumption.

Life cycle inventory During this step, changes in the relevant household constraints of a new or modified product system compared with the reference system should also be captured. If there is no change or even increasing need for household consumption, no positive rebound effect based on consumption-as-usual is possible. Relevant household resources include:

1. Price: Since the financial budget of the household is the main consumption constraint, price reductions lead to rebound effects (cf. Thiesen et al. 2008; Hertwich 2005).
2. Time use: Consumption activities which require the presence of the consuming persons (e.g. mobility, communication, wellness services, and food) allow increasing consumption (rebound) if the speed is increased (cf. Spielmann et al. 2008; Jalas 2005). Some goods like a TV, musical instrument, or soccer ball can use time; however, this is not determined by the product but only by the user.
3. Other household resources: For specific products and consumption categories, other household resources might restrain consumption and therefore be relevant for the rebound effect, such as volume to store goods, saturation (calories) for food, etc. (Hofstetter et al. 2006).

Life cycle impact assessment The environmental impact per functional unit for more of the same can be derived from the life cycle impact assessment itself and the current consumption level (cf. Eqs. 3 and 4). For *more of the similar* and more of other, estimates might differ per region. Based on Eqs. 3 and 6, the change in the environmental impact be can be described as follows

$$\Delta A_{\mathrm{env}}(\mathrm{tot}, \tau_2) = x\left(i^*, t_0\right) \cdot \Delta Y_{\mathrm{env}}\left(i^*, \tau_1\right) + x\left(i^*, t_0\right) \cdot \Delta Y_{\mathrm{res}}\left(j, i^*, \tau_1\right) \cdot Y_{\mathrm{env/res}}(j, \mathrm{tot}, t_0) \quad (7)$$

the first term describes the changing impact due to the product modification of i^*; the second term describes the impact change due to enabled consumption by freed household resource $(x(i^*, t_0) \cdot \Delta Y_{res}(j, i^*, \tau_1))$. The variable, $Y_{\mathrm{env/res}}(j, \mathrm{tot}, t_0)$, denotes the environmental impact per household resources of the increased consumption. Regional values can be estimated by assessing the average consumption, e.g. per country. Table 2 provides such estimates for Switzerland for calories, volume, time, and income rebound. Table 2 shows the feasibility to estimate environmental impact of consuming more of similar or more of other. For specific cases, further refinement could be necessary and possible, for instance regarding which consumption categories are considered as *similar*. In addition, the estimates refer to the time t_0 and therewith do not consider the changing impact intensity of the modified product $\Delta Y_{\mathrm{env}}(i^*, \tau_1)$. For consequential LCA, this can be neglected. However, for attributional LCA, the estimated value needs to be corrected by the improvement of the modified product i^*:

$$Y_{\mathrm{env/res}}(j, \mathrm{tot}, t_1) = Y_{\mathrm{env/res}}(j, \mathrm{tot}) - S_{\mathrm{s}}\left(j, i^*\right) \cdot \Delta Y_{\mathrm{env/res}}\left(j, i^*, \tau_1\right) \quad (8)$$

For a resulting significant positive potential rebound (e.g. RE>10%), the costs in terms of other household resources should also be assessed. These costs can indicate that potential rebound does not develop because of other household constraints. For instance, cheaper cars may not increase driven person-kilometres because car use is often time-limited. Instead in these cases, a switch to higher quality is possible, which can be either larger cars (leading to increased expenditure, but the impact may have lower amplitude compared with driving more; cf. Girod and de Haan 2010), or e.g. hybrid cars (actually leading to lower environmental impact; de Haan et al. 2006; de Haan et al. 2007).

Life cycle interpretation If relevant potential rebound effects are assessed, state (a) how the consumption-as-usual could change the overall environmental improvement; (b) how rebound costs may prevent potential rebound from unfolding; (c) how freed household resources should not be used (more of the same, more of similar, more of other); and possibly (d) how by violation of the assumption (2) of the consumption-as-usual concept of the environmental improvement could be maintained or even increased (e.g. investment of freed resources in lowering impacts). Table 2 shows that the recommendation on the use of freed household resources depends on the consumption purpose and the type of freed household resource. To use freed time for watching TV has nearly the same impact as using it for services. However, freed income is by far better used for services.

3.3 Treatment of rebound effects in LCA studies from the literature

We conducted a literature review looking at various comparative LCA studies. Because changes in price, time use, volume, etc. are not reported, an assessment of the potential rebound is not (always) possible. We restrict ourselves therefore to choosing some examples from different groups of comparative studies with similar rebound effects.

Negative rebound For many environmentally improved products, the price is higher. In this case, the purchase of these products binds additional household resources, and thus, negative rebound occurs. For instance, organic food can result in lower environmental impact per yield compared with conventional food (Maeder et al. 2002), but often also a higher price, which amplifies the benefit for the environment. Similarly, negative time rebound occurs for slow transport modes (cf. Section 3.4).

No rebound For a large group of LCAs, only the production or package of the products changes but consumption costs remain the same (e.g. LCA of beer; Cordella et al. 2008); in these cases, consumption-as-usual is equivalent with constant demand.

Income rebound For price change, a method to consider income rebound has to be proposed (cf. Thiesen et al. 2008).

Time rebound Time rebound could be relevant and changes the picture for different comparative LCA studies. For

Table 2 Estimates for GHG emissions per household resource of Switzerland for assessing the rebound effects

Main categories	Categories	Calories [gCO_2-eq./kcal]	Time [$kgCO_2$-eq./h]	Space [$kgCO_2$-eq./l]	Expenditure [$kgCO_2$-eq./€]
Food	Food, eating out	1.6	–	–	0.4
	Beverages	2.2	–	–	0.4
Living	House/apartment	–	–	–	0.08
	Heating	–	–	–	7.5
	Electricity use	–	0.1[a]	–	3.6
Goods	Furnishings	–	–	0.6	0.7
	Clothes	–	–	2.9	0.2
	Books/news	–	–	2.6	0.3
	Other goods	–	–	0.7	0.6
Mobility	Car, public transport, airplane	–	5.0	–	1.2
Services	Time using services	–	0.1	–	0.04
	Other services	–		–	0.02
Mean[b]		1.7	2.1	0.7	0.5

Emission and expenditure data for the calculation of these coefficients stem from a method using Swiss income and expenditure survey connected with LCA processes (see Girod and de Haan 2009). Household resource use is derived from functional units (see Girod and de Haan 2010) by additional estimates for calories per kilogram of food (FOPH 2005), speed of mobility (Swiss Statistics 2007), and density of goods (from various waste surveys, range 0.1 to 0.2 kg/l)

[a] Only for TV watching (250-W electricity use)

[b] Weighted with relative importance (average household resource use) of different consumption categories

instance, the comparison of the Universal Mobile Telecommunication System (UMTS) and its predecessor the Global System for Mobile Communication would benefit from considering the higher speed of the UMTS, allowing for increasing data demand. The transfer of 1 Gbit is assessed and the UMTS is found to consume 20% less energy (Faist Emmenegger et al. 2006). However, UMTS data transfer is three times faster, hence has a potential time rebound assuming more of the same, which amounts to a factor of eight.[2] Considering actual mobile phone use, the threefold increase in the data demand seems plausible and more robust than a constant demand assumption. For time rebound in personal transport, cf. Section 3.4.

Other rebound Considering other rebound effects, volume rebound might for instance be relevant in the comparison of cathode ray tube and liquid crystal display (LCD) screens (Duan et al. 2009). Since the LCD screen uses less space, it is possible—as in our institute—to have two screens (laptop and additional monitor) or larger screens. Or, the consideration of calories instead of only weight in the comparison of different food supplies would allow to account for diet rebound effects (Jungbluth et al. 2000).

3.4 Illustrative example: rebound for different travel modes

We chose the mobility example since it is will increase in relevance for future environmental impacts (cf. Girod and de Haan 2010). We compare five different travel modes (Table 3), relying on previous work done at our institute (Spielmann et al. 2005; Spielmann et al. 2008; Spielmann and Scholz 2005). Using the car as reference, we compare it to travelling by bicycle, public transport, and airplane. We calculate the average emissions based on ecoinvent data and Swiss prices (see Table 3). The impact reduction (including the rebound effect) is calculated with the proposed method (see Section 3.2). The results show the high time rebound potential of air travel; potential income rebound is also very high. However, public transport also shows significant income rebound potential. The bicycle shows negative time rebound. Costs of increasing demand cannot avoid airplane rebound since time and income rebound are favoured. However, the full amplitude of the time rebound may be dampened by the monetary costs and constant income share used for travelling. Recommendations that can be drawn from these results are first, the consideration of consumption-as-usual makes the airplane a tremendous increase in environmental impact; second, since time use and airplane price are lower, rebound is not restricted by other relevant household resources; third, saved money and time is best used by other activities (except for bicycle).

4 Discussion

The discussion focuses on limitations to our proposed concept to account for rebound effects, first in considering difficulties with cases fulfilling the two underlying assumptions of the consumption-as-usual concept, and second, with possible violations of the assumptions or scope of the concept.

4.1 Challenges in assessing consumption-as-usual

Even if product modification or replacement can be assumed not to change consumption behaviour, determining consumption costs (household resources) and environmental impact of consumption changes may be challenging.

Uncertainty of consumption costs Prices for the same goods and services can vary depending on the region and supplier. In addition, new technologies and also products are often first more expensive and later becomes cheaper. Thus, we can observe first negative and later positive rebound.

Cross-category effects Working with the laptop in the train may lead people to count the time in the train as working time instead of travel time. Thus, the laptop has indirectly freed travel time and thereby increased speed. Such cross-category effects are especially complex for general purpose technologies.

Mental rebound Assuming that households make something like an environmental mental budget, where they try not to exceed a certain limit set by their environmental conscience, an increase in the subjective environmental friendliness of a product will allow the consumer to compensate by buying another more polluting product. This mental rebound could in principle be captured by assuming the mental environmental budget as a household resource (cf. Girod and de Haan 2008). However, the quantification of this effect is difficult and needs further research.

Regarding the distinction between economic growth and the rebound effect, by assuming constant expenditure budgets, the consumption-as-usual approach avoids confounding income increase which would happen anyway

[2] The LCA resulted in primary energy use for 1 Gbit of 800 MJ-eq. (GSM) and 640 MJ-eq. (UMTS). The data rate (speed) of UMTS is indicated as three times that of GSM. The resulting rebound is: $RE = 8 = 1 - (3 \cdot 640 - 800)/(640 - 800)$.

Table 3 Comparison of conventional car, train, conventional airplane, and airplane with increased efficiency

	A: Car	B: Bicycle	C: Regional train	D: ICE	E: Conv. airplane
Impact [gCO_2-eq./pkm][a]	194	4	104	60	154
Price [€/pkm][b]	0.21	0.02	0.05	0.07	0.087
Speed [min/km][c]	1.5	3.5	1.0	0.3	0.15
Reduction of impact [%]	–	98	46	69	21
With time RE (more of the same)	–	99	20	−55	−694
With time RE (more of similar)[d]	–	185	25	18	−37
With time RE (more of other)[d]	–	135	37	47	−4
With income RE (more of the same)	–	77	−135	10	−90
With income RE (more of similar)[d]	–	−15	−49	−12	−51
With income RE (more of other)[d]	–	52	8	36	−9

[a] IPCC 2007 GWP 100a and ecoinvent 2.0 processes: (*A*) 'transport, passenger car/CH', (*B*) 10 kg 'aluminium, production mix, wrought alloy, at plant/RER' and a lifetime of 30,000 km, (*C*) 'transport, regional train, UCPE-MIX/CH', (*D*) 'transport, ICE/DE', (*E*) 'transport, aircraft, passenger/RER'

[b] Prices are based on expenditure and mobility survey (Swiss Statistics 2005, 2007); option D is assumed to be 50% more expensive than C

[c] From mobility survey (Swiss Statistics 2007)

[d] From Table 2 of this study

with the increase in consumption caused by product modification.

4.2 Beyond consumption-as-usual

The limits of the consumption-as-usual concept and therewith the considered rebound effects are given by the scope and the assumptions: Assumption 1 (constant household resource use for consumption) can change over a longer period. For instance, it could also be assumed that freed time is used for non-economic activities (friends, walking, sport, etc.) or freed income to reduce working time. Or, contrary products may lead people to work and spend more on consumption. Considering assumption 2 (constant preferences), we have mentioned that recommendations for 'product use' could influence preferences and therewith the use of freed household resources. In addition, modification of a product could change its desirability; this is especially true if the utility of the product changes. Very emotional or groundbreaking products not only change their own desirability but also influence all other preferences. However, even for these technologies, the consumption-as-usual concept may provide valuable reference and is certainly more accurate than assuming ceteris paribus also for demand in functional units. Finally, the allocation household resources could also be changed by some products. For instance, the small music players (e.g. iPod Nano) allow electronic appliances to access 'new household resource', for instance small trousers pockets. Another example are the new mobile phones allowing communication and even (online) shopping during short breaks. Such new possibilities might have a considerable influence on the preferences.

5 Conclusion

We conclude that applying the consumption-as-usual instead of the constant demand assumption is necessary to assess the overall environmental impact of alternative, more sustainable goods or services. Assuming consumption as usual is the same as applying the ceteris paribus assumption to total household consumption (instead of to total demand for the good or service that is the subject of the LCA in question), which can lead to a consumption feedback loop (rebound effect) due to the reallocation of freed household resources. The illustrative examples showed that the rebound effect can easily offset the intended reduction of environmental impacts partly, in full, or even outweigh them. The proposed method allows integrating such potential rebound effects into ISO-LCA. The advantages are (a) for products with constant or increasing household resource use, the suspicion that they might induce rebound effects can be addressed; (b) for products with potential rebound effects, these adverse effects can be pointed out and recommendations can be formulated as to which household resources have been freed and how they should be used to avoid rebound effects. Strategies for using such freed household resources often involve influencing consumer preferences, for example towards higher-quality products.

6 Recommendations and perspectives

We have proposed a method to assess the occurrence of potential rebound effects and, if such rebound effects seem likely to occur, a method to integrate the effects of such rebound effects into LCA. We believe that taking rebound effects into account will prove beneficial for all LCAs that are related to strategies for more sustainable consumption in general and to changes in consumer behaviour in particular.

Further improvement in the integration of rebound effects into LCA could be attained by (a) assessing the various relevant consumption constraining household resources in order to account for their change in life cycle inventory and (b) determining the average impact of the freed household resources for different consumer samples (e.g. countries and regions). In order to assess not only potential rebound effects but also to forecast the rebound effect for consumption-as-usual, more data on the preferences and reallocation of household resources (not only income) are needed. Furthermore, the assessment of potential rebound makes sense in that it can provide users of assessed products with recommendations on how to use the freed household resources. Also, for improving the consistency of long-term scenarios (Girod et al. 2009), the application of the consumption-as-usual concept would be interesting. Considering the method, future steps should include modelling the consumption-as-usual concept looking also at longer time horizons, and using an optimisation approach or an agent-based approach with a set of different rules to reallocate freed household resources.

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