Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 48 (2016) 336 – 341

www.elsevier.com/locate/procedia

23rd CIRP Conference on Life Cycle Engineering

Market effects in lifecycle assessment: A framework to aid product design and policy analysis

Kate S. Whitefoot[a]* and Steven J. Skerlos[b]

[a]Carnegie Mellon University, 5000 Forbes Avenue, Pittsburgh, PA, 15213
[b]University of Michigan, 500 S. State St, Ann Arbor, MI 48109

* Corresponding author. Tel.:+1-412-268-6771. *E-mail address:* kwhitefoot@cmu.edu

Abstract

Researchers have developed several methods to assess lifecycle environmental impacts of decisions in product design and policymaking. A major challenge is that whether impacts are reduced or exacerbated depends on market effects such as how the design change or policy influences the demand, use, and end-of-life of the relevant product and other products. However, little guidance is available to determine when market effects matter and how to model them. This paper identifies four categories of market effects and presents a framework to help researchers identify *a priori* whether these effects significantly influence environmental impacts and select an appropriate method.

Keywords: life cycle assessment (LCA); market effects; industrial ecology; design for environment; economic ripple effects; system expansion; policy analysis

1. Introduction

The design of products and manufacturing processes is a crucial factor determining the environmental sustainability of a large set of industrial sectors. Automobiles, planes, household appliances, furniture, heating and cooling systems, and processed foods—which together account for 30-50% of total contribution to many environmental impact categories [1]—are all designed products with environmental impacts that are inherently connected to design decisions. Moreover, several life cycle assessment (LCA) studies have found that making different design decisions can reduce various environmental impacts associated with a particular product by 70% or more [2,3].

Recognition of the large role that design decisions have on environmental impacts has triggered a number of policy actions aimed at inducing environmentally preferred design changes. For example, the Corporate Average Fuel Economy regulation in the United States was established to induce automotive designs that have lower fuel consumption. The E.U.'s Waste Electrical and Electronic Equipment directive and Japan's producer take-back requirements aim to encourage product designs that reduce waste streams from disposal [4]. And, both E.U. and U.S. efficiency standards encourage the production of household appliances and consumer electronics that have lower energy use throughout their lifecycles [5].

One critical challenge to assessing the environmental impacts associated with a design decision, and policies seeking to change these decisions, is that they depend to a large extent on the response of many economic agents. Design decisions influence the environment through their influence on producers' manufacturing processes, supply chain sourcing, and the demand, use, and end-of-life of the product and other products. LCA researchers have termed these factors "market effects" or "market mechanisms", referring broadly to economic phenomena that influence decision-makers in the system they are examining [6–9].

In many cases, market effects determine whether or not environmental impacts are reduced or exacerbated. For example, California recently allowed plug-in electric vehicles (PEVs) to use high-occupancy-vehicle (HOV) lanes for

doi:10.1016/j.procir.2016.04.184

single-occupant trips and discontinued these privileges for hybrid vehicles in an attempt to incentivize consumers to purchase PEVs and reduce transportation greenhouse gas (GHG) emissions. The incentive persuaded a significant number of drivers to purchase PEVs primarily for the HOV privileges, but unfortunately, because of differences in their commutes and battery-charging behaviors, these consumers were much less likely to drive the vehicles in electric mode [10]. This caused a significant rebound effect due to the additional weight of the PEV batteries, which increase GHG emissions when they are driven in gasoline mode, enough so that lifetime GHG emissions would be higher than if the consumers drove hybrids instead [11].

The market effects discussed in this paper are distinguished from the industrial interactions captured by Environmental Input Output LCA (EIO-LCA). EIO-LCA is a static representation of the relationships between sectors of an economy which, when taken together, can estimate how consumption of a specific good leads to life cycle environmental emissions by accounting for all sectors necessary to produce, transport, consume, and treat the specific good at its end-of-life [12]. The interactions between sectors in EIO-LCA reflect the aggregate impact of decision-making behavior and structural sectoral dependencies. The market effects considered in this paper are the fundamental supply-demand behaviors and decisions that are ultimately aggregated together and captured in the sector tables used by input-output analysis.

The incorporation of market effects resulting from design decisions (or policies concerned with designed products) is related to “Situation B” in the International Reference Lifecycle Data System (ILCD) Handbook. Situation B represents instances where the decision affects large-scale consequences for the rest of the economy via market mechanisms [13]. However, the current edition of the handbook limits this situation to cases where large-scale consequences are possible that lead to significant additionally installed or decommissioned equipment or production capacity outside of the system of interest. It does not discuss cases where the types and locations of consumers or the production processes of other products significantly change, which as discussed in Sections 2 and 3, are important considerations for LCAs of designed products.

Several methods of incorporating market effects into LCA studies have been developed. However, very little guidance is available to researchers and practitioners to determine when market effects matter, which ones matter most, and what methods are most appropriate to model them. This paper presents a framework to help researchers identify *a priori* whether market effects could significantly influence environmental impacts and select an appropriate method for modelling them. We first review methods of incorporating market effects into LCA studies of designed products. Then, we identify and discuss four categories of market effects that can significantly affect the environmental impacts of designed products. Finally, we present the framework in the form of a flow chart for use during the goal and scope definition of an LCA study.

2. Methods incorporating market effects in LCA

Over the past ten years, researchers have begun developing methods of incorporating market effects into LCA to examine the environmental impacts of design decisions and policies [6,14–17]. Much of this literature builds on the methodological developments in LCA that were constructed to deal with the issues of indirect land-use changes associated with biofuels, and co-product and recycling allocation of metals and other commodities [18–21], extending these developments to the context of designed products. Methods incorporating market effects have been developed for both attributional LCA (aLCA) and consequential LCA (cLCA) approaches.

The existing literature primarily incorporates market effects through one or more of the following methods:

- Expanding the functional unit to the production necessary to satisfy demand in one or more markets;
- Expanding the system boundary to encompass additional products;
- Incorporating endogenous market effects from resulting consumer and producer behavior; and
- Changing exogenous market effects through sensitivity analysis or variation over time.

Expanding the functional unit to the scale of one or more markets allows the LCA researcher to investigate the influence of a design decision on the total demand for the product. Similarly, expanding the system boundary to more than one product allows the researcher to investigate the influence on the production, use, and end-of-life of other products that may be affected by the design decision. For example, Sandén and Karlström [15] analyzed the effect of increasing production of fuel-cell buses in one city on “learning by doing”—the productivity gains that are achieved with experience. The lower price of fuel cells that are induced by this effect increases their diffusion into buses produced in other locales and by other producers, thereby reducing the environmental impacts of these additional products. Market effects considered in LCA studies include effects that are endogenous or “design driven” (meaning that they are affected by the design decision or policy of interest) and those that are exogenous, or determined by factors outside of the system. Table 1 lists several LCA studies of designed products that incorporate market effects, identifying which effects are “design driven” and which are exogenous.

Market effects are modeled in the literature using observed relationships and economic parameters from econometric or experimental studies. Whitefoot et al. [17] modeled the substitution patterns of demand for midsize vehicles depending on the fuel efficiency and acceleration performance of the vehicle by adopting an automotive demand model from the economics literature. Cor and Zwolinski [14,22] modeled the behavior change of users of a coffee-maker by conducting a controlled laboratory experiment observing how users’ behavior changed depending on the design features of the coffee-maker.

Table 1. Literature review of LCA studies of designed products incorporating market effects.

Author(s) and Date	Product	Design decision(s)	Design-driven market effects	Other market effects
Andrae 2015	Various electronic systems	Material selection for components and interconnection substances	-	Increased production of secondary metals in comparison to primary metals
Cor and Zwolinski, 2015	Coffee-maker	Add a screen with energy and water use info, a conservation message, or an automatic switch-off when not in use	The design alternatives induce different levels of behavior change in users affecting energy and water consumption during the use-phase	-
Sandėn and Karlström 2007	City bus	Choice between a fuel cell bus and a diesel bus	Higher demand for fuel cells decreases the technology's cost because of learning-by-doing	-
Stasinopoulos et al. 2012	Car body-in-white (BIW)	Changing a fleet of cars from steel body to aluminum body	Increased output of recycled aluminum at the end of life displaces the use of primary aluminum in BIW production	Demand for cars is assumed to increase over time because of population increase
Whitefoot et al. 2011	Midsize car	Downsizing the engine	Redesigning the engine for higher fuel economy and lower horsepower changes demand for the vehicle and competing vehicles and makes it more profitable for competitors to sell vehicles with higher horsepower engines.	Fuel prices are varied in sensitivity tests, which affect vehicle miles travelled and competitors' profit-maximizing designs
			Vehicle miles travelled changes inversely to fuel savings, increasing for the redesigned vehicle and decreasing for competitors' vehicles	

Economic parameters that have been incorporated into LCA studies to capture market effects, such as substitution patterns and learning curves, often vary with time, location, and the specific context, and are associated with many theories about the behavior of individuals, firms, and markets. Similarly, the results of behavioral experiments are influenced by the experimental context, situational factors, and the participants selected. As such, incorporating the results of econometric or experimental studies into an LCA introduces additional and non-trivial assumptions and/or uncertainty. Despite this, incorporating market effects into the analysis can be preferable to leaving them out in certain circumstances. As with omitting any lifecycle process or indirect effect, not incorporating market effects is equivalent to presupposing these effects have zero or negligible impacts [23]. This can be a poor assumption in some cases, especially when the environmental impacts of market effects are not centered around zero and can dominate direct impacts of the decision, as was the case in the example described in the introduction. As with any LCA study, care must be taken when choosing the constituent models and parameters to ensure that the assumptions and methods used to construct them are appropriate for the purposes of the study, and sensitivity analyses should be conducted to examine the influence of uncertain parameters on the study's results.

3. Which market effects matter and when?

The matrix representation of LCA developed by Graedel et al. [24] and Heijungs [25] provides a useful framework to identify when and what type of market effects matter. In this representation, an LCA can be written as a series of matrix operations. $\boldsymbol{A}$ is the input-output process matrix containing the amounts of intermediate resource and energy inputs required and outputs produced from each process step considered in the analysis. $\boldsymbol{B}$ is the environmental stressor matrix containing the inventories of environmental resources and energy inputs used and emissions and wastes produced from each process step. $\boldsymbol{C}$ is the impact matrix containing the results of the impact assessment, translating each inventory into environmental damages. By defining the vector $\boldsymbol{d}$ as final demand, or the number of final products required to meet the functional unit, and $\boldsymbol{s}$ as the scaling factor that adjusts the unit processes to the number required to meet the final demand, the lifecycle inventories and impacts can be calculated as vectors $\boldsymbol{v}$ and $\boldsymbol{w}$, respectively, from Eq. 1─3.

$$\boldsymbol{s} = \boldsymbol{A}^{-1}\boldsymbol{d} \tag{1}$$

$$\boldsymbol{B}\boldsymbol{s} = \boldsymbol{v} \tag{2}$$

$$\boldsymbol{C}\boldsymbol{v} = \boldsymbol{w} \tag{3}$$

When the market effect resulting from the design decision of interest can alter the demand, the process matrix, stressor matrix, or impact matrix for the designed product or other products such that lifecycle impacts significantly change, it should be considered in the goal and scope definition phase of an LCA study. Each of these categories of market effects is discussed below.

The matrix representation of LCA that we use to identify significant market effects is directly applicable to the aLCA and cLCA approaches. Keeping with the conventions used in these approaches, marginal values would be considered for the process, environmental stressor, and impact matrices in a cLCA whereas average values would be considered in an aLCA. In principle, the framework can also be applied to EIO-LCA by replacing the process matrix (and process effects, described below) with the industry-sector total requirements matrix used in that approach (and market effects that change the total requirements).

3.1. Demand effects

Two classes of demand effects exist that are relevant to LCA. The first is when the decision of interest significantly changes demand for the designed product or another product such as a co-product or a complementary product. The second class is when the decision of interest alters the substitution patterns of demand as demonstrated by Whitefoot et al. [17].

The second class of demand effects can be particularly important to consider because how the design decision affects the types of consumers that use the product and what they would have used instead can dramatically change environmental impacts. For instance, consider Tesla Motor's decision to develop the Model S, an electric high-end sports car. Some industry analysts have indicated that Tesla's nearest competitor is the Porsche Panamera GTS [26]. Assuming this is true, Tesla is luring consumers away from the Panamera, which with a combined fuel consumption of only 19 mpg has much higher lifecycle carbon dioxide emissions than the Model S [27]. If, however, Tesla had chosen to produce an electric compact vehicle like the Nissan Leaf, the reductions in lifecycle emissions compared with likely competitors such as the Nissan Versa would be much smaller.

3.2. Process effects

In addition to the influence a product's design has on its own lifecycle processes, it often influences the lifecycle processes of other products through market effects. The decision to select a particular recyclable material with scarce recycled stocks (say, standard-quality wrought aluminum) for a mass-produced product increases the future availability of recycled stocks that can be used to fabricate other products, assuming the appropriate recycling infrastructure exists [16,28]. When designing a high-volume product, selecting a component that is a differentiated product or is scarce may significantly increase its price, lowering its use in the assembly of other products where cheaper substitutes exist.

These process effects can be captured in LCA by means of commonly estimated economic parameters. The price-elasticities of demand and supply, and the cross-price elasticities can be used to determine how prices change in response to a shift in the supply or demand of the intermediate good, and how changes in its price affect the use of other goods in its place. The scope of the LCA can then be expanded to include additional product(s) whose lifecycle processes are affected by these price changes, adjusting the values of their process matrices accordingly.

3.3. Environmental stressor effects

Market effects can significantly change the inventories of environmental stressors associated with a design decision. The choice to use a heavy or fragile material such as steel or glass in a high-volume product can cause the supplier to locate near the point of production to avoid the high costs of transporting the material [29]. The location-specific availability of materials and energy as well as regulations and conditions affecting emissions and wastes will change the environmental inventories associated with the designed product and other products sourcing from the same supply chain. Similar effects are also possible when the design decision influences the types of consumers that are likely to use the product. For example, if an electric vehicle is designed to appeal to people living in the colder regions of the Midwestern U.S., it will have very different environmental stressors than one designed to appeal to people in the warmer southwest and pacific coast because of differences in battery performance and the electricity mix in these regions [30].

3.4. Impact effects

The impact of an environmental stressor can also be influenced by market effects through differences in the susceptibility of a particular location or population to environmental damages. Mobile phone take-back programs are a good example. Several countries have adopted policies that encourage mobile phone manufacturers to take back unused older phones from their customers with the aim of increasing reuse and recycling and encouraging producers to design them to be more recyclable. Many of the recovered mobile phones were imported to a set of developing countries where demand for second-hand phones was concentrated [31,32]. Unfortunately, when the phones are disposed of in those locations, they have a higher probability of ending up in open dumps or unlined landfills, causing hazardous materials to leach into the environment [32,33]. Impact effects such as this can be incorporated into LCA by examining how the design decision or policy influences the demand from heterogeneous consumers who reside in different locations or have different disposal behaviours as demonstrated by Osibanjo and Nnorom [34].

4. Flow diagram to identify market effects and modeling approaches

Figure 1 presents a flow diagram to guide researchers in determining whether market effects could significantly influence lifecycle impacts as well as applicable methods of incorporating these effects into an LCA study. Methods of incorporating the market effects are given for both aLCA and cLCA approaches. The choice between these approaches is not specified by the diagram but left to the researcher to determine based on the purpose of the LCA.

The flow diagram was developed based on expert opinion informed by the literature review and the four categories of market effects identified in this paper. It is intended as a starting point to aid researchers in defining the goal and scope of an LCA when market effects can potentially influence the system they are examining. Of course, the appropriate inclusion of market effects in LCA will depend on the decision of interest and the specific research questions. Two different research questions may appropriately set the scope of analysis very differently for analyzing the impacts of the same design decision for the same product.

It is important to note that, although the diagram identifies applicable methods of incorporating one or more market effects into an LCA study by drawing upon econometric or

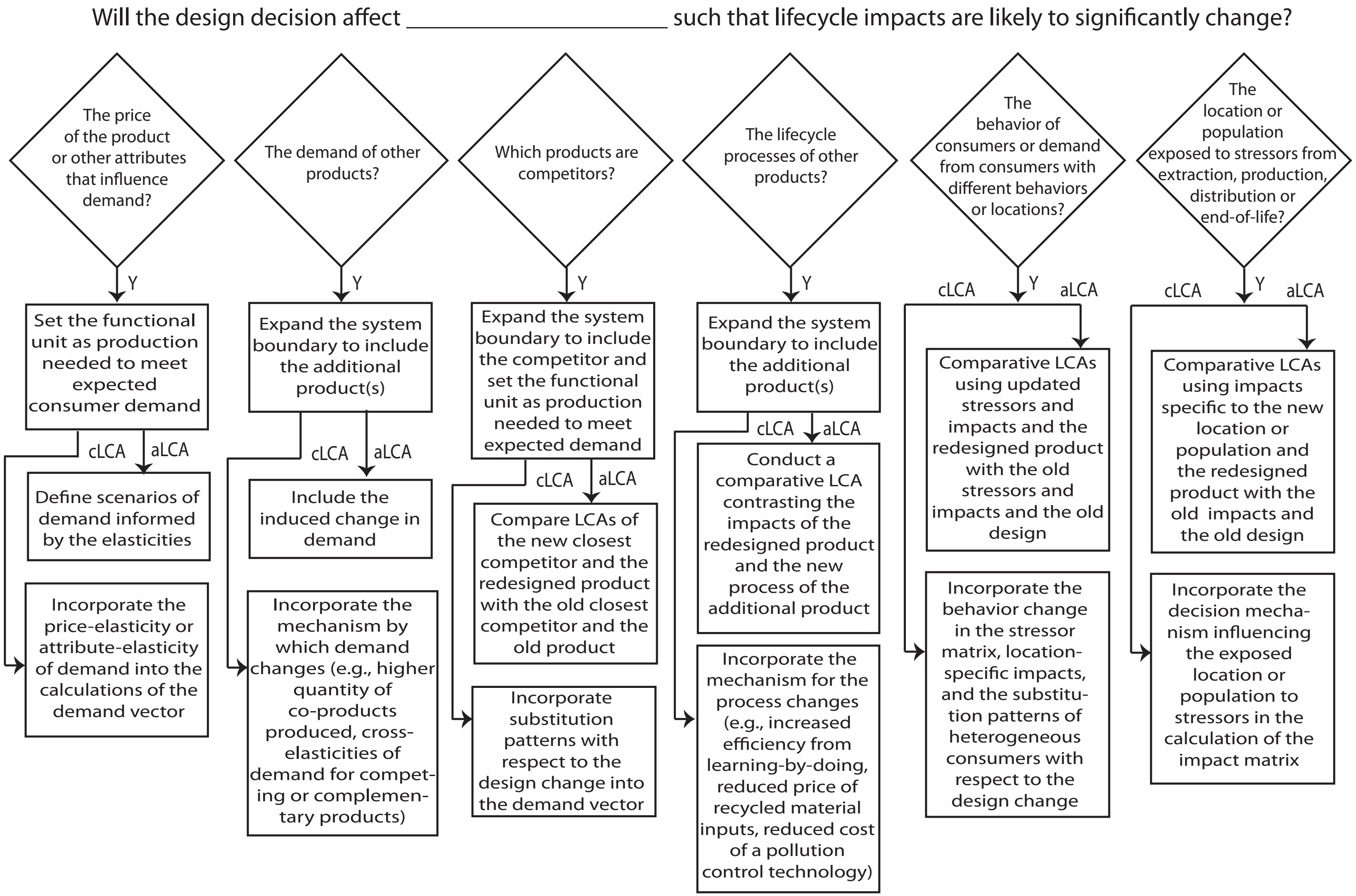

Fig. 1. Flow chart to aid researchers in identifying which market effects are likely to affect lifecycle environmental impacts and applicable modeling methods for attributional lifecycle assessment (aLCA) and consequential lifecycle assessment (cLCA)

experimental studies, the selection of appropriate models and parameters is far from trivial. As discussed in Section 2, many assumptions underlie the construction of these models and parameters and adopting them necessarily means adopting all of these assumptions. In the authors' experience, rigorously modelling market effects in LCA requires multidisciplinary collaborations with scholars that are deeply familiar with the nuanced assumptions and limitations of appropriate economic or behavioral methods describing each market effect.

5. Conclusion

The consideration of market effects in LCA is particularly important when they can significantly alter total environmental impacts resulting from a design or policy decision. In these cases, incorporating market effects can provide useful insights into possible unintended consequences (or substantial benefits) that otherwise may be unforeseen. The four categories of market effects and the flow diagram described in this paper provide a starting point to help LCA researchers conduct this work so that designers and policymakers can mitigate unintended consequences of their decisions and take advantage of hidden opportunities.

Similarly to considering other indirect effects in LCA, rigorous treatment of market effects requires clear characterization of uncertainties and assumptions. Future developments in uncertainty analysis and critical review by experts qualified to evaluate appropriate methods of modeling market effects will strengthen the integrity of LCA results.

Acknowledgements

The authors thank Meredith Fowlie and Costa Samaras for their helpful suggestions. This research was supported in part by Carnegie Mellon University and the National Science Foundation (CMMI 0628162). All conclusions are the authors and do not necessarily represent the funders' views.

References

[1] Tukker, A., Jansen, B., Environmental impacts of products. *J. Ind. Ecol.* 2006, 10, 159–182.
[2] Hittinger, E., Mullins, K.A., Azevedo, I.L., Electricity consumption and energy savings potential of video game consoles in the United States. *Energy Effic.* 2012, 5, 531–545.
[3] Pina, C., Elduque, D., Javierre, C., Martínez, E., Jiménez, E., Influence of mechanical design on the evolution of the environmental impact of an induction hob. *Int. J. Life Cycle Assess.* 2015, 20, 937–946.
[4] Directive 2002/96/EC of the European Parliament and of the Council of 27 January 2003 on waste electrical and electronic equipment (WEEE). *Off. J. Eur. Union* 2003, 46, L37/24–39.
[5] Directive 2005/32/EC of the European Parliament and of the Council establishing a framework for the setting of ecodesign requirements for energy-using products. *Off. J. Eur. Union* 2005, 48, L191/29–58.
[6] Andrae, A.S.G., Method based on market changes for improvement of comparative attributional life cycle assessments. *Int. J. Life Cycle Assess.* 2015, 20, 263–275.
[7] Frees, N., Crediting aluminium recycling in LCA by demand or by disposal. *Int. J. Life Cycle Assess.* 2008, 13, 212–218.
[8] Sathre, R., Chester, M., Cain, J., Masanet, E., A framework for environmental assessment of CO2 capture and storage systems. *Energy* 2012, 37, 540–548.
[9] Zamagni, A., Guinée, J., Heijungs, R., Masoni, P., Raggi, A., Lights and shadows in consequential LCA. *Int. J. Life Cycle Assess.* 2012, 17, 904–918.
[10] Tal, G., Nicholas, M.A., *Exploring the Impact of High Occupancy Vehicle (HOV) Lane Access on Plug-in Vehicle Sales and Usage in California*, 2015. UC Davis Institute of Transportation Studies Report UCD-ITS-RR-14-16.
[11] Shiau, C.-S.N., Samaras, C., Hauffe, R., Michalek, J.J., Impact of battery weight and charging patterns on the economic and environmental benefits of plug-in hybrid vehicles. *Energy Policy* 2009, 37, 2653–2663.
[12] Lave, L., Hendrickson, C., Horvath, A., Joshi, S., Economic input-output models for environment life-cycle assessment. *Env. Sci Technol* 2002, 32, 184–191.
[13] Centre, E.C.J.R., *ILCD Handbook: General Guide for Life Cycle Assessment: Detailed Guidance*, Publications Office of the European Union, 2010.
[14] Cor, E., Zwolinski, P., A Procedure to Define the Best Design Intervention Strategy on a Product for a Sustainable Behavior of the User. *Procedia CIRP* 2014, 15, 425–430.
[15] Sandén, B.A., Karlström, M., Positive and negative feedback in consequential life-cycle assessment. *J. Clean. Prod.* 2007, 15, 1469–1481.
[16] Stasinopoulos, P., Compston, P., Newell, B., Jones, H.M., A system dynamics approach in LCA to account for temporal effects—a consequential energy LCI of car body-in-whites. *Int. J. Life Cycle Assess.* 2012, 17, 199–207.
[17] Whitefoot, K.S., Grimes-Casey, H.G., Girata, C.E., Morrow, W.R., et al., Consequential life cycle assessment with market-driven design. *J. Ind. Ecol.* 2011, 15, 726–742.
[18] Ekvall, T., A market-based approach to allocation at open-loop recycling. *Resour. Conserv. Recycl.* 2000, 29, 91–109.
[19] Finnveden, G., Hauschild, M.Z., Ekvall, T., Guinée, J., et al., Recent developments in Life Cycle Assessment. *J. Environ. Manage.* 2009, 91, 1–21.
[20] Searchinger, T., Heimlich, R., Houghton, R.A., Dong, F., et al., Use of U.S. Croplands for Biofuels Increases Greenhouse Gases Through Emissions from Land-Use Change. *Science* 2008, 319, 1238–1240.
[21] Weidema, B., Avoiding co-product allocation in life-cycle assessment. *J. Ind. Ecol.* 2001, 4, 11–33.
[22] Cor, E., Zwolinski, P., A Protocol to Address User Behavior in the Eco-Design of Consumer Products. *J. Mech. Des.* 2015, 137, 071413.
[23] Plevin, R.J., Jones, A.D., Torn, M.S., Gibbs, H.K., Greenhouse Gas Emissions from Biofuels' Indirect Land Use Change Are Uncertain but May Be Much Greater than Previously Estimated. *Environ. Sci. Technol.* 2010, 44, 8015–8021.
[24] Graedel, T.E., Allenby, B.R., COMRIE, P., Matrix approaches to abridged life cycle assessment. *Environ. Sci. Technol.* 1995, 29, 134A–139A.
[25] Heijungs, R., A generic method for the identification of options for cleaner products. *Ecol. Econ.* 1994, 10, 69–81.
[26] Ed Hellwig, Porsche Panamera GTS vs. Tesla Model S Track Test. *Edmunds.com* 2012.
[27] Weis, A., Jaramillo, P., Michalek, J., Consequential life cycle air emissions externalities for plug-in electric vehicles in the PJM interconnection. *Environ. Res. Lett.* 2016, 11, 024009.
[28] McMillan, C.A., Skerlos, S.J., Keoleian, G.A., Evaluation of the Metals Industry's Position on Recycling and its Implications for Environmental Emissions. *J. Ind. Ecol.* 2012, 16, 324–333.
[29] Smith, Donald, Florida, Richard, Agglomeration and industrial location: An econometric analysis of Japanese-affiliated manufacturing establishments in automotive-related industries. *J. Urban Econ.* 1994, 36, 23–41.
[30] Tamayao, M.-A.M., Michalek, J.J., Hendrickson, C., Azevedo, I.M., Regional Variability and Uncertainty of Electric Vehicle Life Cycle CO2 Emissions across the United States. *Environ. Sci. Technol.* 2015, 49, 8844–8855.
[31] Mooallem, J., The Afterlife of Cellphones. *N. Y. Times* 2008.
[32] Ongondo, F.O., Williams, I.D., Cherrett, T.J., How are WEEE doing? A global review of the management of electrical and electronic wastes. *Waste Manag.* 2011, 31, 714–730.
[33] Osibanjo, O., Nnorom, I.C., Material flows of mobile phones and accessories in Nigeria: Environmental implications and sound end-of-life management options. *Environ. Impact Assess. Rev.* 2008, 28, 198–213.
[34] Skerlos, S.J., Morrow, W.R., Chan, K., Zhao, F., et al., in:, *IEEE Int. Symp. Electron. Environ.*, IEEE, 2003, pp. 99–104.