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Application of fuzzy logic for the integration of environmental criteria in ecodesign

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ABSTRACT

The ecodesign of a product implies that different potential environmental problems of diverse nature must be considered, apart from the general design criteria (i.e., technical, functional, ergonomic, aesthetic or economical). In this sense, an ecodesign tool integrating the criteria provided by three environmental evaluation methodologies, namely Ecological Footprint (EF), Life Cycle Assessment (LCA) and Environmental Risk Assessment (ERA), has been constructed on the basis of fuzzy logic reasoning and features. This idea enabled the decision making at process and product level taking into account the values of the different indicators at a time. The relative importance of each of them has been established through the definition of membership functions as inputs to the fuzzy inference reasoning procedure in the case of a specific product. As a result, a Fuzzy EcoDesign Index (FEcoDI) was obtained. A well known case study was used to test the tool. Different packaging materials for a beverage bottle were considered to identify the most environmentally friendly option.

1. Introduction

Ecodesign may be defined as the systematic introduction of environmental concerns during product design and development (AENOR, 2003). This means to bear in mind the environmental impacts at all stages of the product life cycle, starting at the designing and development phases. The objective is to create sustainable solutions that satisfy human needs and desires (Karlsson & Luttropp, 2006). The identification and appraisal of the environmental burdens requires the application of evaluation tools. The different available indicators offer complementary visions of the studied scenario; therefore, they can not be replaced by each other and, in most cases, more than one should be applied at a time (Byggeth & Hochschorner, 2006).

The EF provides valuable information about the degree of sustainability of a particular process since this indicator especially accounts for resources and energy consumption. However, some limitations were acknowledged for this methodology (Kitzes & Wackernagel, 2009; Kitzes et al., 2009), even though active development on EF methodology poses to continuous new proposals to overcome core critiques (Herva, Hernando, Carrasco, & Roca, 2010; Herva, García-Diéguez, Franco-Uría, & Roca, in press; Venetoulis & Talberth, 2008). Thus, the EF does not capture most of the impact categories usually applied in life cycle analysis or it does not comprehensively take into account waste and emission flows. As a consequence, it results interesting to complement EF studies with certain Life Cycle Assessment (LCA) indicators (Herva, Franco, Ferreiro, Álvarez, & Roca, 2008), depending on the case study. Besides, the existence of a relation between EF and LCA has been identified by Huijbregts et al. when the Ecoindicator 99 was employed to evaluate a large number of products and services (Huijbregts, Hellweg, Frischknecht, Hungerbühler, & Hendriks, 2007).

LCA is claimed to offer an integrative assessment of a process; however, the information provided regarding human and ecosystem toxicity, for example, is more incomplete than desirable. This means that it has a limited capacity to predict toxicity effects given that the fate of pollutants is usually not considered, so that the calculated impacts are potential rather than actual (Azapagic & Perdan, 2000). Risk assessment, on the other hand, provides an established methodology based on the appraisal of different scenarios and events, distribution and transfer routs, exposure pathways, duration and frequency of the events that allows for a more rigorous and exhaustive evaluation. Nevertheless, assessments may need to integrate the risks from the entire life cycle of the chemical or product (Van Leeuwen, 2007). Therefore, LCA and ERA are complementary tools that can be integrated (Leet Socolof & Geibig, 2006). In fact, motivated by the increasing release of pollutants in production processes, the European Union has carried out an integration of the risk and Life-Cycle Assessment tools named USES-LCA (Huijbregts et al., 2000). ERA is used to estimate a risk index associated to certain hazardous substances that raw materials may contain (organic compounds, heavy metals, etc.) and that would affect the final consumers or factory employees (Franco, Costoya, & Roca, 2007).

The integration of the indicators derived from the application of the environmental evaluation tools Ecological Footprint (EF), Life

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Cycle Assessment (LCA) and Environmental Risk Assessment (ERA) is proposed. They show complementary characteristics when applied in the evaluation of products and processes, thus making their integration very appealing.

When more than one indicator is handled at a time, the difficulty arises when a decision has to be made based on the information provided by all of them. Methodologies of multi-criteria analysis have proved to be efficient in the definition of integrative frameworks, but their application requires processing imprecise, uncertain, qualitative or vague data. FL is one of the most common methodologies used to address uncertainty matters (Bellman & Zadeh, 1970). The use of fuzzy logic techniques allows obtaining a quantitative approach using a qualitative representation (Zadeh, 1965); thus, it is able to simultaneously handle numerical data and linguistic knowledge (Carrasco, Rodríguez, Puñal, Roca, & Lema, 2002).

FL techniques have been applied in a number of studies in the environmental field. Ocampo-Duque, Ferré-Huguet, Domingo, and Schuhmacher (2006) developed a Fuzzy Water Quality (FWQ) index calculated with fuzzy reasoning and using AHP (Analytical Hierarchy Process) for weight assignment to the variables involved in the rules, thus defining the relative importance and influence of the input parameters in the final score. This final index integrated a wide set of indicators including organic pollution, nutrients, pathogens, physicochemical macro-variables, and priority micro-contaminants, and was intended to assess water quality in rivers. Similarly, Sadiq and Husain (2005) proposed the use of a fuzzy-based methodology and a three-stage hierarchical structure for estimating aggregative risk of various environmental activities, pollution sources and routes in a given process. The developed methodology was applied to a case study of offshore drilling waste for evaluating various discharge scenarios. Phillis and Andriantiatsaholiniaina (2001) developed a model called Sustainability Assessment by Fuzzy Evaluation (SAFE) in which ecological and human inputs were treated individually and then combined with the aid of fuzzy logic to provide an overall measure of sustainability (Andriantiatsaholiniaina, Kouikoglou, & Phillis, 2004).

Marchini, Facchinetti, and Mistri (2009) presented F-IND, a user-friendly software framework for the development of multivariable indices with fuzzy approach. The framework was suitable for any kind of ecological system (e.g. air, soil, water) and could be used for evaluation of quality, vulnerability, sustainability, impact magnitude or any other ecosystem property. This allowed environmental technicians not familiar with the theoretical fundamentals of fuzzy logic to convert their expert knowledge into the desired fuzzy index in a simple way.

The fuzzy multi-objective model proposed by Kuo, Wub, and Shieh (2009) aimed at considering not only environmental criteria through a LCA, but also the customer needs and cost considerations in the ecodesign of products. They developed an eco-quality function deployment (Eco-QFD) to aid product design teams in seeking the overall customer satisfaction.

In the present work, a framework based on the integration of EF, LCA and ERA was proposed. This approach was built on the basis of fuzzy logic (FL) reasoning and features. The objective was to obtain a final Fuzzy EcoDesign Index (FEcoDI) for ranking options from an environmental point of view. To test the tool, two packaging materials for a water bottle were evaluated.

2. Materials and methods

2.1. Case study

The case study is based on a 2 l bottle of drinking water as functional unit. Two kinds of plastic materials were assessed: PET and PVC. Based on the life cycle inventory of these products (Table 1), EF and complementary LCA were estimated. For ERA, particular acknowledged risk problems were taken into account, like the migration of bisphenol A (Le, Carlson, Chua, & Belcher, 2008) and aldehydes in PET (Dabrowska, Borcz, & Nawrocki, 2003), or vinyl chloride monomer in PVC (Fayad, Sheikheldin, AlMalack, ElMubarak, & Khaja, 1997).

2.2. Methodologies of the ecodesign tools employed

For the EF assessment the component approach, based on local data and Life Cycle Assessment studies, was employed (Monfreda, Wackernagel, & Deumling, 2004). Thus, individual EFs were calculated for each material and energy flow in the inventory data, and then they were aggregated to estimate the total EF of each bottle. This indicator was employed to evaluate the energy and materials consumption in the production process of the product.

Emissions released during the manufacture were evaluated via LCA. In this case, the methodology established in the ISO 14040 standards was applied (ISO, 2006). During the life cycle impact assessment, only the compulsory characterization phase was considered in the development of the ecodesign framework. However, the normalization phase was also conducted in order to obtain environmental impacts prioritization criteria. Characterization and normalization factors from the Dutch Institute of Environmental Sciences (CML) were applied in Eqs. (1) and (2), respectively (CML, 2000).

$$C_j = \sum_i C_{ij} = \sum_i A_i \cdot W_{ij} \tag{1}$$

$$C_{j,N} = C_j / N_j \tag{2}$$

where A_i is the amount of emission i released, W_{ij} is the characterization factor for the emission i within the category j, C_{ij} is the contribution of the emission i to the category j, C_j is the characterized value of the category j, N_j is the normalization factor of the category j and $C_{j,N}$ is the category j normalized. C_j units depend on the category considered, whereas $C_{j,N}$ is dimensionless.

Global Warming Potential (GWP) and Acidification Potential (AP) impact categories were incorporated into the EF estimate using absorption factors. For the conversion of CO_2 equivalent emissions into area units, a factor of 1.42 tC ha^{-1} yr^{-1} was employed (Wackernagel & Rees, 1996); meanwhile, for the transformation of acidifying emissions a critical load of 20×10^{-3} eqH^+ m^{-2} yr^{-1}, which is a general threshold for Europe, was applied (Holmberg, Lundpvist, Robèrt, & Wackernagel, 1999).

For the environmental risk estimates, migration rates from the bottle material to water, as well as final concentrations in water for the compounds considered (bisphenol A, vinyl chloride monomer and aldehydes), were found in the literature (Table 2).

The concentration of these compounds in water stored depended mainly on initial concentrations in the bottle material, as well as on temperature and time of storage. Estimations were made under the worst case scenario conditions (i.e., major concentrations reported) and only considering the oral pathway. Thus, during the exposition evaluation phase, Eq. (3) was used to estimate the daily dose due to ingestion of water:

$$Dose = WIF \cdot CW \tag{3}$$

where *Dose* is expressed in mg kg^{-1} day^{-1}, *WIF* is the human water intake factor – a value of 2.5×10^{-2} l kg^{-1} day^{-1} was considered (Clark, Cousins, & Mackay, 2003) – and *CW* is the final concentration in water of each compound expressed in mg l^{-1}.

For the risk characterization, reference doses (*RfDs*) for non carcinogenic effects, and slope factors (*SF*) for carcinogenic effects, were used in order to calculate the Hazard Quotient (*HQ*) and the

Table 1
Inventory data for the PVC and PET systems (Feijoo & Roca, 2005).

			PVC		PET	
Input variables	Raw materials	Iron ore	0.0118	g	13.75	g
		Limestone	4.8	g	6.75	g
		Sand	0.032	g	0.5	g
		Water	640	g	438	g
		Bauxite	7.11	mg	7.75	mg
	Energy		1.978	MJ	1.868	MJ
Output variables	Air emissions	CO_2	57.6	g	53	g
		CH_4	0.182	g	0.0925	g
		N_2O	0.0002	g	0.0001	g
		NO_x	0.511	g	0.475	g
		SO_x	0.416	g	0.55	g
		Halon 1301	0.0012	mg	0.0018	mg
		Metals	0.0438	mg	0.0174	mg
		Aromatic compounds	1.487	mg	0.087	mg
		Others	0.0081	g	0.0028	g
	Water emissions	COD[a]	0.0352	g	0.0780	g
		Phosphates	0.0022	g	0.0022	g
		Nitrates	0.0003	g	0.0003	g
		Ammonium	0.0005	g	0.0008	g
		Others	0.0083	g	0.0027	g
	Solid waste		4.16	g	1.03	g

[a] COD: Chemical Oxygen Demand.

Table 2
Data used for the risk characterization.

Compound	Material	Migration rate/concentration in water			RfDs[a] mg kg^{-1} day^{-1}	SF[a] kg day^{-1} mg^{-1}
		Value	Units	Source		
Bisphenol A	PET	0.19 ± 0.13	μg l^{-1}	Le et al. (2008)	5.00×10^{-2}	–
Vinyl monomer	PVC	0.6	μg l^{-1}	Fayad et al. (1997)	3.00×10^{-3}	1.50
Acetaldehyde	PET	60.0 ± 6.0	μg l^{-1}	Dabrowska et al. 2003	–	–
Formaldehyde	PET	78.1 ± 7.8	μg l^{-1}	Dabrowska et al. 2003	2.00×10^{-1}	–

[a] Source: (ORNL, 2010).

Cancer Risk factor (*CR*) as stated in Eqs. (4) and (5) (ORNL, 2010; USEPA, 2010).

$$HQ = Dose/RfDs \tag{4}$$

$$CR = Dose \cdot SF \tag{5}$$

HQ and *CR* values calculated for the different compounds are summed up for each material to obtain the final indexes. The result must keep under maximum acceptable levels of 1 and 10^{-4}, respectively.

The EF, LCA and ERA methodologies were implemented in a spreadsheet in MS Excel® 2003.

2.3. Fuzzy logic structure

The use of FL techniques allows meshing a quantitative approach using a qualitative representation (Carrasco et al., 2002). The most important features of FL are that it uses linguistic variables and that knowledge is represented by if-then linguistic rules. A linguistic variable is defined by four items: (1) the name of the variable; (2) its linguistic values; (3) the membership functions of the linguistic values; (4) the physical domain over which the variable takes its quantitative values (Phillis & Andriantiatsaholiniaina, 2001).

The linguistic variables in this case were those corresponding to the indicators derived from the application of the environmental evaluation methodologies explained previously. Given that the most important LCA environmental impacts were GWP and AP (obtained in the normalization phase), and they could be integrated into the EF value, membership functions were defined for CR, HQ and EF. The EF contribution to the ecodesign indicator was measured in terms of EF variation (ΔEF) in relation to a base case; that is to say, the higher the decrease in the EF value, the better.

Triangular and trapezoidal functions were selected in all cases. These are the simplest membership functions and they are formed using straight lines. The triangular function is nothing more than a collection of three points forming a triangle. The trapezoidal membership function has a flat top and it just really consist of a truncated triangle curve. These straight line membership functions have the advantage of simplicity, but provide detail enough to describe the input variables considered in this case.

The Mamdani inference system (Mamdani & Assilian, 1975) was selected and the Fuzzy Logic Toolbox of Matlab® v.7.7 was used to develop the ecodesign tool. Mamdani's fuzzy inference method is the most commonly seen fuzzy methodology. Besides, Mamdani-type inference expects the output membership functions to be fuzzy sets. On the other hand, Sugeno-type systems can be used to model any inference system in which the output membership functions are either linear or constant.

Table 3
Typical examples of the if-then rules defined.

IF	THEN
CR *is* Unacceptable	FEcoDI *is* Unacceptable
CR *is* High *and* HQ *is* High	FEcoDI *is* Unacceptable
CR *is* Low *and* HQ *is* High *and* ΔEF *is* Average *or* Bad	FEcoDI *is* Bad
CR *is* Low *and* HQ *is* Low *and* ΔEF *is* Bad	FEcoDI *is* Average
CR *is* Low *and* HQ *is* Medium *and* ΔEF *is* Good	FEcoDI *is* Good

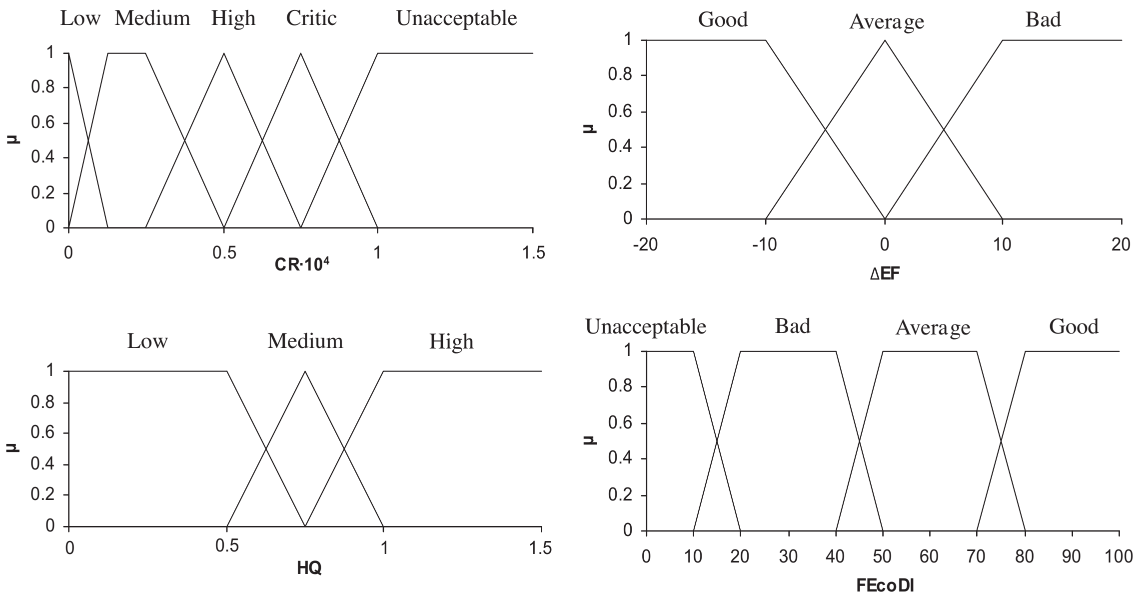

Fig. 1. Membership functions for input variables (CR, HQ, EF) and for the output FEcoDI.

A total of 23 if-then rules were defined and implemented. Some of these rules are shown in Table 3 as an example.

As output to the inference engine, a Fuzzy EcoDesign Index (FEcoDI) was obtained, which collected the different criteria given by the tools used. The best option, from an overall environmental point of view, will be the one with the highest FEcoDI (Fig. 1).

3. Results and discussion

On the basis of the inventoried data for the manufacture of a 2 l bottle of these materials, the EF and ACV were calculated, the former accounting for materials and energy consumption, and the latter for emissions to air and water. LCA results for the characterization and normalization phase are shown in Table 4 and Fig. 2, respectively. Observing the major importance of GWP and AP categories, and the low relevance of Ozone Depletion Potential (ODP) and Eutrophication Potential (EP) categories, the latter were discarded from this first approach of the ecodesign tool. After the integration of these two into the EF estimates using absorption factors, the total amount of productive land required resulted in 2.27 m^2/bottle for PVC and 2.43 m^2/bottle for PET. Since in the fuzzy structure EF is measured in terms of variance with respect to a base case, the lowest value of the two (PVC) was considered as reference level. Consequently, the input for the PET bottle would correspond to a 7% increase in relation to the EF of the PVC bottle.

Results from ERA were collected in Table 5. Although acetaldehyde and formaldehyde have the R40 risk phrase associated (ESIS, 2010), this meaning that there is limited evidence of a carcinogenic effect (they are catalogued as carcinogenic type 3), currently there is no slope factor available recognized by and international organization for these substances. Furthermore, acetaldehyde has neither RfDs nor SF; thus, it was not possible to assess the potential environmental risk contribution of this compound. The HQ and CR were below the safety limits stated by the US-EPA in all cases. It must be noticed that in the case of PET the risk contribution of two compounds was considered, while for the PVC only the potential risk derived from the vinyl monomer migration was appraised. This was made according to main risk problems acknowledged in the literature, and taking into account that the purpose of the analysis was to test the tool, not to present definite results on the evaluation of the two materials.

The results obtained applying each environmental evaluation methodology were introduced into the ecodesign tool. As a result,

Table 4
Characterization phase for PVC and PET bottle.

Impact category	Units	PVC	PET
GWP	g CO_2 eq	61.5	55.0
AP	g SO_2 eq	0.75	0.90
ODP	g CFC eq	1.44×10^{-5}	2.16×10^{-5}
EP	g PO_4 eq	6.96×10^{-2}	6.60×10^{-2}

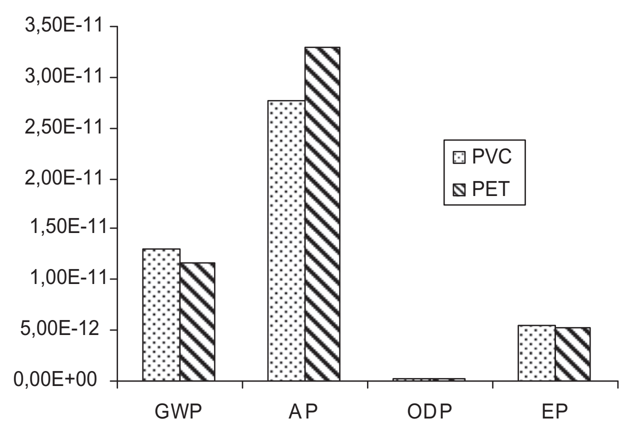

Fig. 2. Normalization phase for PVC and PET bottle.

Table 5
Results for the Environmental Risk Assessment.

Material	Compound	HQ	CR
PET	Bisphenol A	9.50×10^{-5}	–
	Formaldehyde	9.76×10^{-3}	–
	Total	9.86×10^{-3}	–
PVC	Vinyl monomer	5.00×10^{-3}	2.25×10^{-5}

a FEcoDI of 30.0 for the PVC bottle was obtained, while a value of 66.6 was estimated for the PET bottle. Consequently, this would lead to select the PET bottle as the best option from an environmental point of view.

The main difference between the two materials studied was the existence of a carcinogenic slope factor for the vinyl monomer. In the definition of membership functions, the universe of discourse for CR was divided into more categories than for the other variables. The CR has a probabilistic nature; this means that if it has a value different from zero, a risk of someone suffering from cancer will exist. However, in the case of HQ, effects on exposed population will occur only if the reference dose is exceeded. As a result, fewer precautions were taken for HQ values lower than 1, while for the CR a more strict characterization was considered. The tool seemed to be sensitive to changes in the EF only when CR and HQ were low enough. This may be because of the way the decision tree was constructed, first evaluating the CR and then the HQ, and only allowing the EF appraisal of those products that had passed the first barriers. Therefore, materials that may cause carcinogenic effects will receive a bad evaluation from the tool. Thus, in this case, the PET bottle obtained a better FEcoDI in spite of having a higher EF and HQ. The revision of this imbalanced weight for the input variables may lead to variations in the structure of the decision tree in the fuzzy reasoning. It could be more adequate to expand the number of levels for the HQ membership function in order to properly differentiate between products with different risk characteristics under the safety limits (HQ = 1), depending on the case study.

4. Conclusions

A first approach of a tool based on EF, LCA and ERA was built on the basis of fuzzy logic reasoning and features. The output obtained was a Fuzzy EcoDesign Indicator (FEcoDI) that could range between 0 and 100, and that collected the criteria offered by the different environmental evaluation methods. In general terms, the constructed tool seemed to work properly. However, when testing it with a real case some limitations were detected and further development is proposed. The following steps may be considered: (a) integration of more LCA impact categories that may be significant in the evaluation of other products; (b) a refinement of the decision tree in the fuzzy reasoning; and (c) a revision in the number of categories defined in the universe of discourse of HQ.

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References

AENOR (2003). Environmental Management of Design and Development Process. Design for Environment, UNE 150301 Standards (in Spanish).

Andriantiatsaholiniaina, L. A., Kouikoglou, V. S., & Phillis, Y. A. (2004). Evaluating strategies for sustainable development: Fuzzy logic reasoning and sensitivity analysis. *Ecological Economics, 48*, 149–172.

Azapagic, A., & Perdan, S. (2000). Indicators of sustainable development for industry: A general framework. *Process Safety and Environmental Protection, 78*(4), 243–261.

Bellman, R. E., & Zadeh, L. A. (1970). Decision-making in a fuzzy environment. *Management Science, 17*, 141–163.

Byggeth, S., & Hochschorner, E. (2006). Handling trade-offs in ecodesign tools for sustainable product development and procurement. *Journal of Cleaner Production, 14*, 1420–1430.

Carrasco, E. F., Rodríguez, J., Puñal, A., Roca, E., & Lema, J. (2002). M. Rule-based diagnosis and supervision of a pilot-scale wastewater treatment plant using fuzzy logic techniques. *Expert Systems with Applications, 22*, 11–20.

Clark, K., Cousins, I. T., & Mackay, D. (2003). Assessment of critical exposure pathways. In C. A. Staples (Ed.), *The handbook of environmental chemistry* (pp. 227–262), vol. 3, part Q. Springer, Berlin (Germany).

CML (Institute of Environmental Sciences). CML 2 baseline 2000 V2.3.

Dabrowska, A., Borcz, A., & Nawrocki, J. (2003). Aldehyde contamination of mineral water stored in PET bottles. *Food Additives and Contaminants, 20*(12), 1170–1177.

ESIS (2010). European chemical substances information system. http://ecb.jrc.it/esis/, Last accessed June 2010.

Fayad, N. M., Sheikheldin, S. Y., AlMalack, M. H., ElMubarak, A. H., & Khaja, N. (1997). Migration of vinyl chloride monomer (VCM) and additives into PVC bottled drinking water. *Journal of Environmental Science and Health, Part A, 32*, 1065–1083.

Feijoo, G., & Roca, E. (2005). Environmental Technologies. In Hercules de Ediciones, A Coruña (Ed.), *Galicia Ecology*, vol. XLVII: Environmental Science and Technology I. Part II: Technology for environmental protection (pp. 403–427), Spain, (in Spanish).

Franco, A., Costoya, M. A., & Roca, E. (2007). Estimating risk during showering exposure to VOCs of workers in a metal-degreasing facility. *Journal of Toxicology and Environmental Health, Part A, 70*, 627–637.

Herva, M., García-Diéguez, C., Franco-Uría, A., & Roca, E. (in press). New insights on ecological footprinting as environmental indicator for production processes. *Ecological Indicators*.

Herva, M., Franco, A., Ferreiro, S., Álvarez, A., & Roca, E. (2008). An approach for the application of the ecological footprint as environmental indicator in the textile sector. *Journal of Hazardous Materials, 156*, 478–487.

Herva, M., Hernando, R., Carrasco, E. F., & Roca, E. (2010). Development of a methodology to assess the footprint of wastes. *Journal of Hazardous Materials, 180*, 264–273.

Holmberg, J., Lundpvist, U., Robèrt, K.-H., & Wackernagel, M. (1999). The ecological footprint from a systems perspective of sustainability. *International Journal of Sustainable Development and World Ecology, 6*, 17–33.

Huijbregts, M. A. J., Hellweg, S., Frischknecht, R., Hungerbühler, K., & Hendriks, A. (2007). Ecological footprint accounting in the life cycle assessment of products. *Ecological Economics, 64*, 798–807.

Huijbregts, M. A. J., Thissen, U., Guinèe, J. B., Jager, T., Kalf, D., van de Meent, D., et al. (2000). Priority assessment of toxic substances in life cycle assessment. Part I: Calculation of toxicity potentials for 181 substances with the nested multi-media fate, exposure and effects model USES-LCA. *Chemosphere, 41*, 541–573.

ISO (2006). International Organization for Standardization. ISO 14040 Standards. www.iso.org., Last accessed July 2010.

Karlsson, R., & Luttropp, C. (2006). EcoDesign: what's happening? An overview of the subject area of EcoDesign and of the papers in this special issue. *Journal of Cleaner Production, 14*, 1291–1298.

Kitzes, J., Galli, A., Bagliani, M., Barrett, J., Dige, G., Edef, S., et al. (2009). A research agenda for improving national ecological footprint accounts. *Ecological Economics, 68*, 1991–2007.

Kitzes, J., & Wackernagel, M. (2009). Answers to common questions in ecological footprint accounting. *Ecological Indicators, 9*, 812–817.

Kuo, T.-C., Wub, H.-H., & Shieh, J.-I. (2009). Integration of environmental considerations in quality function deployment by using fuzzy logic. *Expert Systems with Applications, 36*, 7148–7156.

Le, H. H., Carlson, E. M., Chua, J. P., & Belcher, S. M. (2008). Bisphenol A is released from polycarbonate drinking bottles and mimics the neurotoxic actions of estrogen in developing cerebellar neurons. *Toxicology Letters, 176*, 149–156.

Leet Socolof, M., & Geibig, J. R. (2006). Evaluating human and ecological impacts of a product life cycle: The complementary roles of life-cycle assessment and risk assessment. *Human and Ecological Risk Assessment, 12*, 510–527.

Mamdani, E. H., & Assilian, S. (1975). An experiment linguistic synthesis with a fuzzy logic controller. *International Journal on Man–Machine Studies, 7*(1), 1–13.

Marchini, A., Facchinetti, T., & Mistri, M. (2009). F-IND: A framework to design fuzzy indices of environmental conditions. *Ecological Indicators, 9*, 485–496.

Monfreda, C., Wackernagel, M., & Deumling, D. (2004). Establishing national natural capital accounts based on detailed ecological footprint and biological capacity assessments. *Land Use Policy, 21*, 231–246.

Ocampo-Duque, W., Ferré-Huguet, N., Domingo, J. L., & Schuhmacher, M. (2006). Assessing water quality in rivers with fuzzy inference systems: A case study. *Environment International, 32*, 733–742.

ORNL (2010). Risk Assessment Information System (RAIS). Oak Ridge National Laboratory, Oak Ridge, TN, USA. http://rais.ornl.gov/, Accessed June 2010.

Phillis, Y. A., & Andriantiatsaholiniaina, L. A. (2001). Sustainability: An ill-defined concept and its assessment using fuzzy logic. *Ecological Economics, 37*, 435–456.

Sadiq, R., & Husain, T. (2005). A fuzzy-based methodology for an aggregative environmental risk assessment: A case study of drilling waste. *Environmental Modelling & Software, 20*, 33–46.

USEPA (2010). Integrated Risk Information System (IRIS); http://www.epa.gov/iris/, Accessed June 2010.

Van Leeuwen, C. J. (2007). General introduction. In *Risk assessment of chemicals: An introduction*, pp. 1–36). Dordrecht (The Netherlands): Springer.

Venetoulis, J., & Talberth, J. (2008). Refining the ecological footprint. *Environment, Development and Sustainability, 10*, 441–469.

Wackernagel, M., & Rees, W. (1996). *Our ecological footprint: Reducing human impact on the Earth*. New Society: Gabriola Island, British Columbia.

Zadeh, L. (1965). Fuzzy sets. *Information and Control, 8*, 338–353.