Life Cycle Impact Assessment Weights to Support Environmentally Preferable Purchasing in the United States

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LCA is a quantitative method for understanding the environmental impacts of a product, yet all product purchasing decisions are ultimately subjective. Weights are the nexus between the quantitative results of LCA and the values-based, subjective choices of decision makers. In May 2007, NIST introduced a new optional weight set in Version 4.0 of the BEES software. Three key points about this new optional weight set are the basis for discussion in this paper: The new weight set was created specifically in the context of BEES. It is intended to support a practical method to assist environmentally preferable purchasing in the United States based on LCIA results. This is in contrast to the weight sets currently in BEES, which are based on generalist perspectives. The new weight set was created by a multi-stakeholder panel via the AHP method, and is a synthesis of panelists' perspectives on the relative importance of each environmental impact category in BEES. The weight set draws on each panelist's personal and professional understanding of, and value attributed to, each impact category. While the synthesized weight set may not equally satisfy each panelist's view of impact importance, it does reflect contemporary values in applying LCA to real world decisions, and represents one approach others can learn from in producing weight sets. The new weight set offers BEES users an additional option for synthesizing and comparing the environmental performance of building products and making purchasing decisions. In so doing, it strengthens the decision-making process, which is important when making product comparisons in the public domain. The Weight Set: Across all panelists and with explicit consideration of all time horizons, anthropogenic contributions to global warming, weighted at 29%, was judged most important, yet not so important that decisions can be made solely on the basis of this impact. A strong tail of other concerns include fossil fuel depletion (10%), criteria air pollutants (9%), water intake/use (8%), human health cancerous effects (8%), ecological toxicity (7%), eutrophication of water bodies (6%), land use (6%), and human health noncancerous effects (5%). Also of interest are the identified impact areas of concern assigned the lowest weights: smog formation (4%), indoor air quality (3%), acidification (3%), and ozone depletion (2%). Their low weights may indicate that there is not as much immediate concern or that the remedial actions associated with the impact for the most part are underway.

Introduction

Life cycle assessment (LCA) is a science-based, quantitative method for evaluating the environmental impacts of a product, yet all overall environmental performance assessments are ultimately subjective because few products are likely to out-perform alternatives across all impact categories. To reconcile these likely performance tradeoffs, the optional LCA step of weighting may be employed to enable synthesis of performance scores for all impact categories considered into a single score. Weights are the link between the quantitative results of LCA and the values-based, subjective choices of decision makers.

In May 2007, NIST introduced a new optional weight set in Version 4.0 of the BEES (Building for Environmental and Economic Sustainability) software (*1*) as shown in Figure 1. Weighting schemes available in earlier versions of the tool were based on an equal weighting and two generalist perspectives: U.S. EPA Science Advisory Board (SAB) and Harvard University's Kennedy School of Government (*2*, *3*). A summary of the weights available in BEES is shown in Table 1. Although the SAB- and Harvard-based weightings are valuable and offer guidance from a broad base of constituents, several interpretations and assumptions were required for use as LCA-based weights.

The BEES software implements a consistent, systematic technique for selecting environmentally preferable, cost-effective building products. The technique is based on consensus standards and designed to be practical, flexible, and transparent. This decision support tool is aimed at designers, builders, and product manufacturers and includes environmental and economic performance data for building products across a range of functional applications.

BEES measures the economic and environmental performance of building products using publicly sanctioned methods of decision making. Environmental performance measures are based on the LCA approach specified in ISO 14040 standards (*4*, *5*). All stages in the life of a product are analyzed: raw material acquisition, manufacture, transportation, installation, use, and waste management. Economic performance is measured using the ASTM International standard life-cycle cost method (ASTM E 917), which covers the costs of initial investment, replacement, operation, maintenance and repair, and disposal. Environmental and economic performance measures are combined into an overall performance measure using the ASTM standard for Multiattribute Decision Analysis (E 1765-2) (*6*−*8*).

The current version of BEES computes performance scores for twelve environmental and human health impact categories. The impact categories included in BEES are primarily based on the U.S. EPA's Tool for the Reduction and Assessment of Chemical and other Environmental Impacts (TRACI) life cycle impact assessment (LCIA) methodology, with one additional category, indoor air quality (IAQ),

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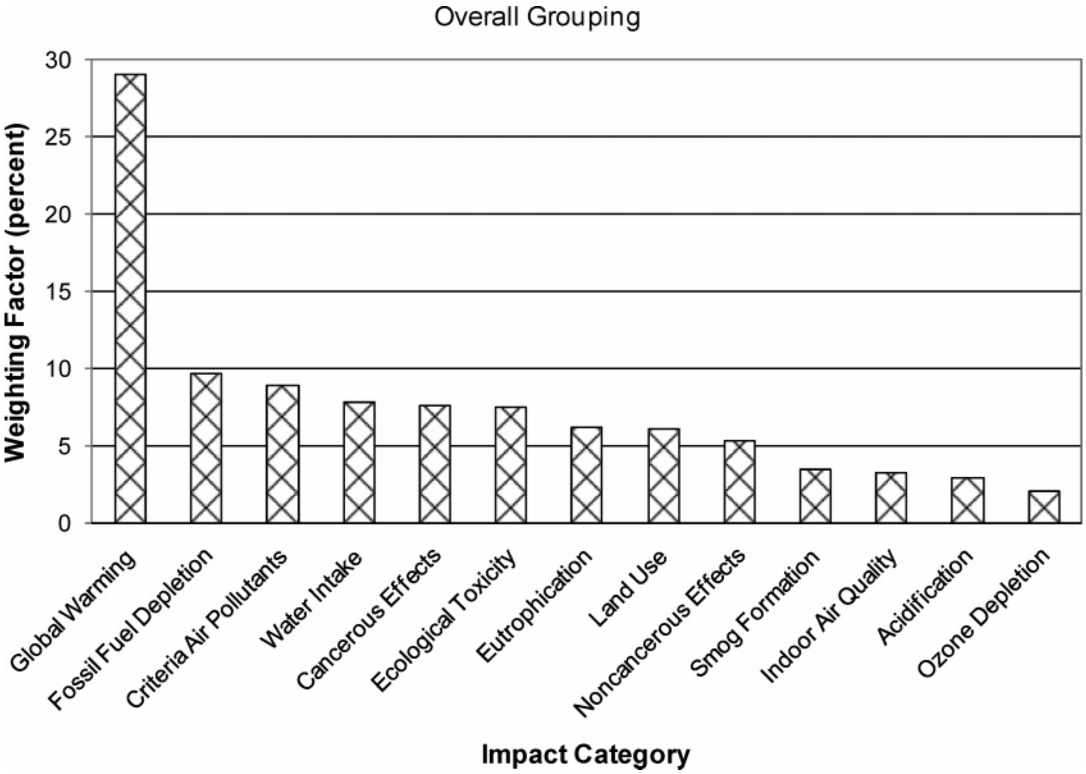

FIGURE 1. General environmentally preferable purchasing weights.

developed specifically for the purpose of tailoring the coverage of impacts to building and construction elements (*1*, *9*).

To compare the overall environmental performance of competing products, BEES synthesizes the performance scores for all impact categories into a single score. This is done through weighting, a value-based process that represents the scientific interpretation and ideological, political, and ethical principles. The motivation for employing weighting is based on the desire to simplify LCIA output, especially in circumstances where trade-offs across a product system occur. There are critics of LCA who argue that LCA should be an objective environmental evaluation procedure. This topic has been discussed exhaustively elsewhere (*10*−*12*). Others have evaluated in detail issues deriving and justifying value choices in LCA (*13*−*20*).

For this application it is clearly recognized that weighting is a subjective, value-based process. Further, it is recognized that it is necessary to use weighting in order to conform to the ISO 14044 requirement that a "comprehensive set of environmental issues related to the product system being studied shall be reflected" when conducting an LCA study (*5*).

In order to develop this set of weights, NIST solicited input from a volunteer stakeholder panel. This paper presents the weight results from this stakeholder panel employing the Analytic Hierarchy Process (AHP)—as described by ASTM Standard E 1765-2 (*7*).

Approach

NIST assembled a stakeholder panel that met at its facilities in Gaithersburg, Maryland, May 2006 to develop a new optional weight set for BEES version 4.0. To convene the panel, invitations were sent to individuals representing one of three "voting interests": producers, users, and LCA experts, see Figure 2. Nineteen individuals participated in the panel: seven producers, seven users, and five LCA experts. These "voting interests" were adapted from ASTM International

Voting Interests of Individuals Invited to Participate in BEES Stakeholder Panel

The three general classifications of individuals invited to participate in the BEES stakeholder panel included:

- Producer – An individual who represents an organization that produces or sells building materials, products, systems or services
- User – An individual who purchases or represents an organization that purchases or uses building materials, products, systems or services
- LCA Expert – An individual who does not fit into any of the preceding categories *and* is recognized for his/her LCA expertise

* *classifications adapted from ASTM International*

FIGURE 2. Voting interests of participants.

groupings for developing voluntary standards that support a consensus process (*21*).

Prior to the panel exercise, all panelists received a briefing paper introducing the BEES software, the purpose for establishing a new weight set, the rationale for a stakeholder panel, a description of the process the panel would follow, preparation procedures, and references for background reading. The stakeholder panel was facilitated by Dr. Ernest Forman, Expert Choice Inc., who introduced the AHP process through a series of warmup exercises. Next, panelists discussed among themselves the scope and intricacies of their specific task. A number of questions and concerns were discussed and agreed upon. Following this discussion, Dr. Forman facilitated panelists in weighting the impact categories via the AHP method. The panel first weighted all

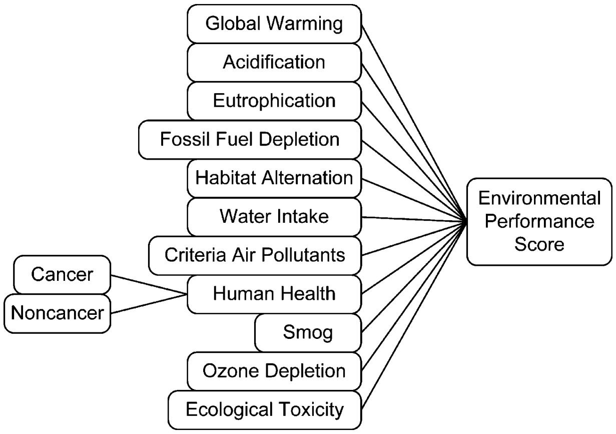

FIGURE 3. Impacts contributing to the BEES environmental performance score.

impacts in the "long term" and then paused to view, analyze, discuss, and revise the synthesized results.

Subsequently, the panel weighted impacts in the "short term" and then in the "medium term". The meaning of these terms is clarified in the following discussion on the AHP process. At the close of the day, panelists were asked to complete a feedback form, which was collected by NIST.

AHP Method. The AHP was developed in the 1970s by Thomas L. Saaty and has since come into the mainstream of conventional multiattribute decision analysis (*22*, *23*). It is a systematic approach to finding the priorities of a range of decision criteria and then measuring the contribution of potential solutions to those criteria. In the context of BEES, the AHP is used to develop a set of importance weights for environmental impacts so that life cycle impact assessment results may be synthesized to measure overall environmental performance for alternative building products (*7*). Details of the mathematical formulation and methodology of the AHP process can be found in Saaty (*23*).

Hierarchy. The AHP organizes a decision problem into a hierarchy consisting of a goal and contributing decision criteria. The goal of the BEES hierarchy for environmental performance measurement is environmentally preferable purchasing. Contributing to that goal are twelve decision criteria, namely, the BEES environmental impacts as shown in Figure 3 (*1*). For the LCA Stakeholder Panel event, Cancerous and Noncancerous effects were judged separately to yield a more refined weight set than BEES 3.0 (*24*).

Pair-Wise Comparisons. In the absence of quantitative data indicating the importance or preference of one impact over another, the AHP employs a procedure of paired comparisons. One year's worth of U.S. flows (e.g., annual emissions, energy use, and water demand by the entire U.S. economy) for each pair of impacts is compared over three time horizons: Short Term (0−10 years), Medium Term (10−100 years), and Long Term (100+ years). For example, for an impact comparison over the Long Term, the panel was evaluating the effect that this year's U.S. emissions would have more than 100 years hence.

When making pair-wise comparisons the panel participant also expresses the intensity of that importance. Table 2 shows an "intensity of importance" scale developed by Saaty. He has demonstrated that only the whole numbers 1 through 9 are necessary to indicate the intensity of preference, with a 1 meaning that the two items being compared are of equal importance and a 9 meaning the first item is extremely important compared to the second. Table 2 shows how the AHP translates verbal judgments ranging from "equal importance" to "extreme importance" into intensity scores of 1, 3, 5, 7, or 9, with 2, 4, 6, and 8 as intermediate values between adjacent judgments.

TABLE 1. Summary of Weights Available in BEES

impact category	EPP Weights	Science Advisory Board	Harvard[a]	equal
Global Warming	29.3	16	11	8.3
Fossil Fuel Depletion	9.7	5	7	8.3
Criteria Air Pollutants	8.9	6	10	8.3
Water Intake	7.8	3	9	8.3
Human Health Canerous	7.6	11	6	8.3
Human Health Noncancerous	5.3			
Ecological Toxicity	7.5	11	6	8.3
Eutrophication	6.2	5	9	8.3
Habitat Alteration	6.1	16	6	8.3
Smog	3.5	6	9	8.3
Indoor Air Quality	3.3	11	7	8.3
Acidification	3.0	5	9	8.3
Ozone Depletion	2.1	5	11	8.3

[a] This Harvard University 1992-based weight set is not available in BEES 4.0.

When comparing decision criteria in the AHP hierarchy, one needs to frame questions so they elicit the decision maker's view of the importance of one element over another. For example, a value of 3 means that the decision maker considers today's global warming emissions to be moderately more important than today's acidification emissions in the long term. The reciprocal comparison receives a value of 1/3.

Relative Weights. The solution technique of the AHP takes as inputs the values generated by the pair-wise comparisons and produces, as outputs, the relative weights of the decision criteria. To obtain the relative weights of the elements, the AHP normalizes the principle eigenvector and interprets it as the vector of priorities that indicates the importance of each element with respect to a criterion in the next higher level.

Consistency. The relationship between the pair-wise comparison values and the relative weights is mathematically exact if the judgments are perfectly consistent. The presence of slight inconsistency in judgments can be recognized by the AHP. For example, the scale value of 9 should remain approximately three times as favorable as the scale value of 3, but if Fossil Fuel Depletion is judged twice as important as Smog, and Smog three times as important as Ozone Depletion, then the final ranking is not influenced much if Fossil Fuel Depletion is not strictly six times as important as Ozone Depletion (*26*). It has been shown that small deviations from consistent judgments do not change the relative weights by much; information from all pair-wise comparison values contributes to the calculation of the weights (*27*).

In the AHP, small changes in some values will be offset by changes in other values because there are redundant judgments. Large inconsistencies, however, may reverse the ranking of decision alternatives. The AHP, therefore, includes a measure of the departure from consistency, called the consistency ratio. The consistency ratio is a value between 0.00 for perfectly consistent pair-wise comparisons and 1.00 for randomly generated comparisons. A ratio of 0.10 or less indicates a high level of consistency. While a ratio between 0.10 and 0.15 is considered acceptable, it indicates that a review of pai-wise comparison judgments may be warranted. If it is higher than 0.15, it is advisable to reexamine the judgments and eliminate the most obvious inconsistencies.

Limitations. The AHP method has been used for applications as diverse as energy policy formulation, marketing, accounting and auditing, subjective probability estimation, and evaluation of expert systems. One criticism raised against the AHP concerns the requirement to explicitly state and incorporate subjective judgments. This requirement is rejected by some members of the operations research and

TABLE 2. Description of Pair-Wise Comparison Judgment Scale (*25*)

intensity of importance	definition	explanation
1	equal importance of elements	two elements contribute equally to the higher-level element
3	moderate importance of one element over another	experience and judgment slightly favor one element over another
5	strong importance of one element over anothe	experience and judgment strongly favor one element over anothe
7	very strong importance of one element over another	an element is strongly favored and its dominance is demonstrated in practice
9	extreme importance of one element over another	the evidence favoring one element over another is of the highest possible order of affirmation
2, 4, 6, & 8	intermediate values between two adjacent judgments	used when compromise is needed between two judgments
	reciprocals	if element i has one of the above numbers assigned to it when compared with element j, then j has the reciprocal value when compared with i.

TABLE 3. Environmental Impact Importance (%) by Voting Interest and Time Horizon

	all time horizons (100%)				short-term time horizon (24%)				medium-term time horizon (31%)				long-term time horizon (45%)			
impact category	all	producer	user	LCA expert	all	producer	user	LCA expert	all	producer	user	LCA expert	all	producer	user	LCA expert
global warming	29	16	30	50	7	5	9	7	43	26	43	60	52	30	57	68
fossil fuel depletion	10	12	7	10	15	13	12	15	7	13	3	13	4	10	1	5
criteria air pollutants	9	7	6	13	18	11	11	48	2	3	3	1	1	2	0	1
water intake	8	7	10	5	7	7	8	3	10	8	14	6	8	8	9	6
cancerous	8	8	6	6	8	11	6	5	6	4	6	4	9	9	6	7
ecological toxicity	8	8	11	3	6	5	9	2	9	12	11	3	9	9	13	5
eutrophication	6	8	6	3	8	8	9	4	6	10	5	5	3	4	2	2
land use	6	6	9	3	7	7	11	3	6	6	8	3	5	6	6	3
noncancerous	5	11	4	2	6	12	5	3	4	6	2	2	6	17	2	2
smog formation	4	4	3	2	7	6	6	4	1	3	1	1	0	1	0	1
indoor air quality	3	5	3	1	7	9	6	4	1	1	1	1	0	0	0	0
acidification	3	4	4	1	4	6	6	1	2	4	2	1	2	2	2	1
ozone depletion	2	3	2	1	2	3	3	1	2	4	2	1	2	3	1	1
inconsistency	0.03	0.05	0.03	0.05	0.04	0.06	0.06	0.05	0.02	0.04	0.02	0.06	0.06	0.11	0.08	0.13

management science communities, who are reluctant to adopt a method that does not claim to be purely "objective." Harker and Vargas (*28*) explain that trends in philosophy of science support the view that subjectivity plays a role in scientific analysis linking scientific method, cognition, and belief. They draw attention to the fact that all preference-eliciting methods have to deal with the problem of ambiguity. The AHP allows decision makers to comprehend the issue at hand and use its structure to meaningfully address it.

Advantages. The AHP is well suited to facilitate interpretation of LCIA results. It does so by arranging and comparing decision criteria in such a way that decision makers can logically and consistently evaluate all of the criteria in a complex decision problem. By presenting decision makers with a single environmental performance score for each product alternative, it encourages emerging markets for environmentally friendly products without overly burdening purchasers with too much information. Saaty and other researchers do not insist that the AHP is the only valid method to analyze decision problems. Despite inherent limitations, AHP remains a useful approach among several aids to decision making that involves qualitative or intuitive judgments, too unstructured for traditional numerical techniques (*29*).

Results

The environmental impact importance weights developed by the AHP technique at the panel event are tabulated in Table 3 and displayed in Figures 4 and 5. Table 3 displays the weights computed for all combinations of stakeholder grouping and time horizon. When synthesizing judgments across stakeholders and time horizons, all panelists were assigned equal importance, while the short-, medium-, and long-term time horizons were determined to carry 24%, 31%, and 45% of the weight, respectively.

Figure 4 shows weights specific to panelists from the three voting interests: producers, users, and LCA experts. Note that the AHP consistency ratios for all groupings were 0.05 or less, indicating a high level of consistency.

Figure 5 shows how the panel's weights change when impact categories are compared with reference to different time horizons: Long Term (100+ years), Medium Term (10−100 years), and Short Term (0−10 years). While this year's U.S. emissions for only two impacts (global warming and ecological toxicity) grow in importance over time, three impacts (cancerous effects, noncancerous effects, and water intake) fluctuate in importance, ozone depletion is insensitive to time, and the remaining seven impacts decrease in importance over time.

Discussion

Weight Set. Across all panelists and time horizons, contributions to global warming (29%) was judged most important, yet not so important that decisions can be made solely on the basis of this impact. Other concerns include fossil fuel depletion (10%), criteria air pollutants (9%), water intake (8%), human health cancerous effects (8%), ecological toxicity (7%), eutrophication (6%), land use (6%), and human health noncancerous effects (5%). Also of interest are the identified impact areas of concern assigned the lowest weights: smog formation (4%), indoor air quality (3%), acidification (3%), and ozone depletion (2%). Their low weights may indicate lack of immediate concern or that the remedial actions associated with the impact, for the most part, are underway.

The most striking finding is that stakeholder grouping does matter, particularly among the three groups formulated

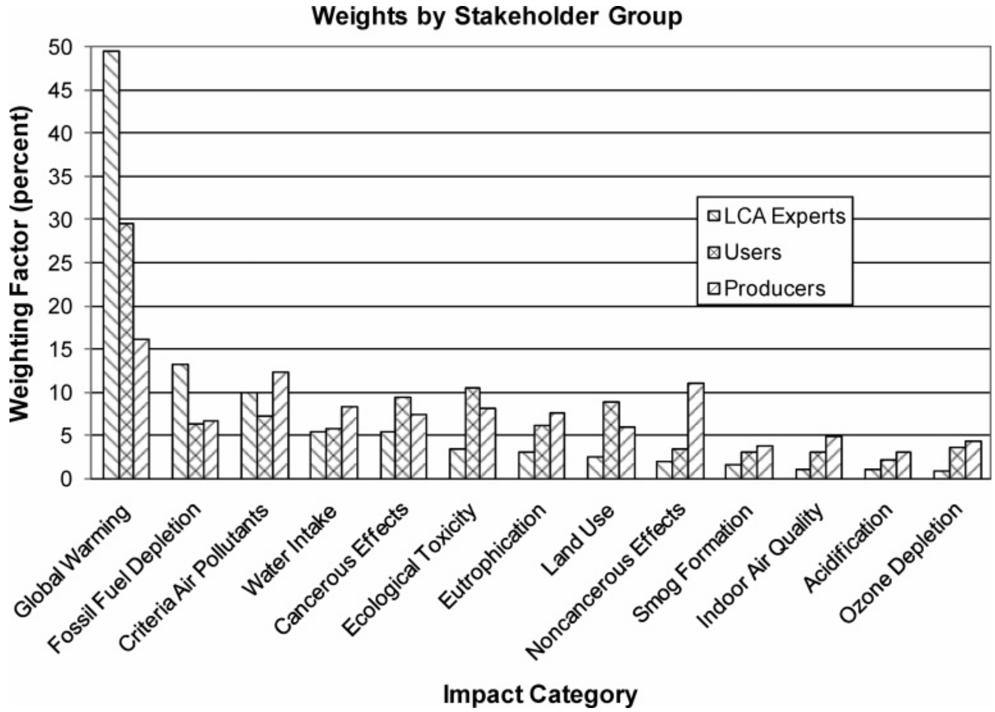

FIGURE 4. Environmental impact importance by stakeholder group.

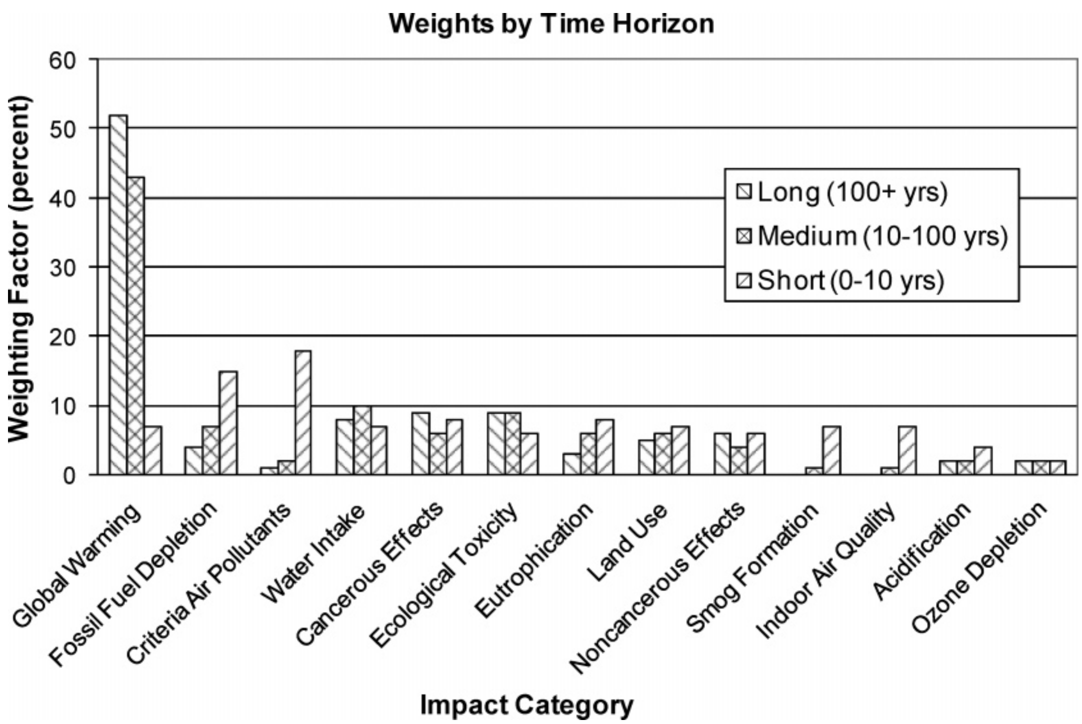

FIGURE 5. Environmental impact importance by time horizon.

for the volunteer panel: producers, users, and LCA experts. Producers were inclined to weight impacts fairly evenly: global warming (16%), fossil fuel depletion (12%), and non-cancerous human health (11%). The tail of the distribution was robust as well, with the lowest weight for ozone depletion (3%).

Users were inclined to rate global warming highest (30%), nearly double the weight of producers for this impact. Impact areas following global warming included ecological toxicity (11%), water use (11%), and land use (10%). The higher rating of ecological toxicity was justified by this group of panelists from a precautionary principle perspective, whereby known limitations of the current state-of-the-science of LCIA were cause to assign a higher weight to the impact category, not lower.

Although familiar with the comprehensive nature of their discipline, LCA experts were far more variable in assigning weights, assigning a weight to global warming highest (early 50%), with the next highest weight Human Health Criteria pollutants (13%). Including the third highest weight, fossil fuel depletion at 10%, would represent a collective weight of 79% for the top four issues. The five lowest categories were weighted at 2% and below.

In addition to synthesizing weights delineated by panel member interest, weights were synthesized by time horizon. In the short-term, human health effects associated with emission of criteria pollutants (31%) and fossil fuel depletion (21%) were weighted the highest, with the next highest weights being global warming and eutrophication, both at (12%). In the medium- and long-term, global warming was weighted the highest (45% and 50%, respectively), with ecological toxicity and water use the next highest.

Panelists' Engagement and Discovery Process. While some panelist feedback was conflicting, all agreed that the opportunity to raise and discuss issues throughout the day was invaluable. Panelists found these discussions to be nuanced, informative, and thought-provoking, ultimately leading to more meaningful results, as demonstrated when, early in the day, the panel agreed to modify both the goal and the structure of the decision hierarchy.

The goal of the decision hierarchy was initially limited to "environmentally preferable building product purchasing." Panelists agreed that the building industry's products need not be distinguished from other products, and that it would be useful to develop weights at the U.S. level. Therefore, panelists modified the goal to "environmentally preferable U.S. purchasing."

Panelists also discussed and modified the structure of the hierarchy to be assessed. The goal noted above and the three objectives contributing to that goal were to be the three areas of impact: Natural Resource Use, Human Health Effects, and Natural Environment Protection. Each objective in turn had its own contributing environmental impacts for which LCA results may be developed. Panelists modified this structure after agreeing that grouping environmental impacts based on three time horizons, rather than by area of impact would yield the most useful weight set.

Realizing the Potential Significance of the Task at Hand. Panelists expressed and discussed a number of concerns related to their understanding of their roles and the ultimate application of the results.

Some were concerned they did not fully understand the AHP method and expressed desire to have had more time to learn the AHP before conducting the actual weighting exercise. Alternatively, some panelists felt time spent explaining the method would have been better spent making and discussing their subsequent pair-wise comparison judgments. Other panelists expressed concern over the varying degree of understanding, and interpretation, of each impact category: was their understanding of a particular impact category consistent with the other panelists' and, if not, would the process accommodate differences? In particular, several panelists questioned the inclusion of the impact categories Land Use and Water Intake based on the relatively poor quality of their underlying measurement methods. For instance, some felt the factors encompassed by "land use" were insufficient, as they did not account for the degree of reversibility of the land disruption.

Future Directions. Panelists were asked whether future LCA Stakeholder Panels should be convened to develop weights on a bio-regional scale. Almost all responded in the affirmative, noting that such panels should take place in, and consist of residents from, the corresponding bio-region, and even at the global scale. While the purpose of the event was to develop a U.S. average set of importance weights for a range of environmental impacts and this purpose was served, most agreed that the process and the stimulating discussions held throughout the day turned out to be equally valuable.

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