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An Integrated Approach for the Management of Uncertainty in Decision Making Supported by LCA-Based Environmental Performance Information

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Abstract: This paper presents an approach for the integrated consideration of both technical and valuation uncertainties during decision making supported by LCA-type environmental performance information. Key elements of this approach include “distinguishability analysis” to determine whether the uncertainty in the performance information is likely to make it impossible to distinguish between the activities under consideration, and the use of a multivariate statistical analysis approach, called principal components analysis (PCA), which facilitates the rapid analysis of large numbers of parallel sets of results, and enables the identification of choices that lead to similar and/or opposite evaluations of activities. The integrated approach for the management of uncertainty is demonstrated for a technology selection decision for the recommissioning of a coal-based power station. Distinguishability analysis showed that it was not possible to obtain a conclusive answer with regard to the preferred technology due to the extensive uncertainty in the LCA-based environmental performance information. PCA of the ranking of the design scenarios demonstrated that valuation uncertainties associated with choices made during intra- and inter-criterion preference modelling had a more significant effect on the ranking of the design scenarios than the inclusion/exclusion of environmental indicators reflecting local concerns or the choice of the position of the LCIA impact indicators in the cause-effect network. The results suggest that stakeholder involvement in intra- and inter-criterion preference modelling is important, and that the “encoding” of value judgements and preferences into LCA environmental performance information is to be avoided. As a whole, the paper supports a call for diversity in LCA methodology rather than one for greater standardisation, and provides a foundation for the consideration of the implications of such methodological diversity as part of an overall approach to promote effective decision making based on LCA environmental performance information.

Keywords: Decision Making; Valuation; Uncertainty; Multivariate Statistical Analysis

1. INTRODUCTION

Life Cycle Assessment (LCA) has gained recognition as a tool that can provide environmental performance information to support both decision making in the private and public sectors. The consideration and management of uncertainty is regarded as an essential part of good decision making practice. A distinction can be made between uncertainties that affect the estimation of the potential consequences of the activities under consideration and those that pertain to uncertainties in variables which are used for the evaluation of these consequences [Bonano, 1995]. It is suggested that these uncertainties be described

as “technical uncertainties” and “valuation uncertainties”, respectively. To date, methodological development for LCA has focused on the former, with less consideration being given to valuation uncertainties.

The evaluation of the (environmental) consequences of activities requires the modelling of value judgements, which inform both model structure and the choice of specific parameters in LCA models and in any decision models created to facilitate the comparative evaluation of the activities under consideration. A large number of choices of model structure and model parameters are made in both LCA and decision models. The

consideration of the effects of all valuation uncertainties, in conjunction with technical uncertainties, can thus become an unmanageably large task. This paper presents a comprehensive and efficient approach for the integrated consideration of both technical and valuation uncertainties during decision making supported by LCA-type environmental performance information. The approach is illustrated in the context of a technology selection decision for the recommissioning of a coal-based power station.

2. AN INTEGRATED APPROACH FOR THE CONSIDERATION OF UNCERTAINTY IN DECISION MAKING

2.1 A Foundation in Multiple Criteria Decision Analysis (MCDA)

The integrated approach for the consideration of uncertainties in decision making has been developed to be used in conjunction with an approach to decision support based on multiple criteria decision analysis (MCDA). MCDA [e.g. Belton and Stewart, 2002] is a well-established approach to aid or support decision makers faced with complex decisions. It has been demonstrated that the structure of LCA has parallels with a decision analysis approach to decision making [e.g. Miettinen and Hämäläinen, 1997; Seppälä, 1999; Hertwich and Hammitt, 2001; Seppälä, et al., 2001]. However, more significantly from a decision making point of view, has been the use of MCDA to enable the consideration of trade-offs between environmental performance reflected by LCA-type indicators and performance pertaining to at least one other concern (e.g. financial, technical and/or social issues) and/or to provide an overall indication of the performance of a set of alternatives to facilitate decision making [e.g. Azapagic, 1996; Alexander, et al., 2000]. For discrete decision problems (i.e. ones in which a finite set of alternatives are considered), the use of MCDA methods based on multiple attribute value theory (MAVT) (also called “value function methods”) have been demonstrated to be of particular value to assist in the evaluation of a set of alternatives based on LCA-type environmental performance information [e.g. Miettinen and Hämäläinen, 1997; Seppälä, 1999].

2.2 Key Elements of the Approach

2.2.1 Placing Bounds on Particular Aspects

Uncertainties that are introduced during the problem structuring stage of the decision analysis

process result from choices that define the scope of the decision process. These choices include the definition of the decision problem, the choice of stakeholders, the choice of temporal and spatial system boundaries for modelling of alternatives, and the choice of alternatives for consideration. The suggested approach for the management of these uncertainties is to attempt to achieve consensus amongst those involved in the decision process that appropriate bounds have been placed around the decision problem under consideration. Those who manage to decision process thus need to ensure that the necessary discussion takes place to enable the selection of appropriate bounds, and it is recommended that additional steps that call for the explicit verification of the choices made be introduced into the decision process.

2.2.2 Distinguishability Analysis

There would be little value in commencing with detailed preference modelling for the evaluation of the alternatives unless some of the alternatives are distinguishable from others despite the uncertainty in the performance scores. To ensure such “distinguishability”, it is suggested that a step called “distinguishability analysis” be incorporated into the decision analysis process prior to any evaluation of the performance of the alternatives. Two approaches to distinguishability analysis have been identified, namely principal components analysis (PCA) [e.g. Jackson, 1991] and the “distinguishability index” (DI) approach developed for this purpose by Basson [2004]. In the latter, the potential ranges of the performances of the alternatives are compared in a pairwise manner and an assessment made of the number of aspects in which the performance ranges overlap due to the uncertainty in the performance information compared to the number of aspects in which the performance ranges do not overlap. In this manner it is possible to obtain an overall indication of whether any alternatives are completely distinguishable from any others, and, if not, in which aspects the alternatives are / are not distinguishable from one another.

2.2.3 Sensitivity Analysis

The implications of uncertainties introduced during the problem analysis elements of the decision analysis process, such as the choice of multiple criteria evaluation methods, associated preference models and parameters used in these models, need to be examined via sensitivity analysis. However, as a first pass, this effect of several of the model form- and model parameter- uncertainties may be investigated in a parametric manner to obtain an

overall impression of their relative significance. (See Morgan and Henrion [1990] for parametric approaches for the consideration of model form uncertainties.) Finally, PCA can be applied to samples of the range of potential ranks of the alternatives to enable the graphical comparison the effect of the uncertainties examined through sensitivity analysis.

3. ILLUSTRATION OF THE OVERALL STRATEGY IN THE CONTEXT OF A TECHNOLOGY SELECTION DECISION PROBLEM

3.1 Problem Definition

A decommissioned power station belonging to an electricity supply company is to be recommissioned to meet a projected electricity demand. At issue for the recommissioning of the power station is whether it would be preferable to repower a station with fluidised bed combustion (FBC) boilers burning discard coal rather than to refurbish the existing pulverised fuel (PF) boilers which would burn run-of-mine coal?

The decision situation was originally considered by Notten [2001] in the context of a thesis which focused on data quality and the management of uncertainty in Life Cycle Inventory (LCI) information in resource-based industries. The case study decision presented here draws from Notten's work for the definition of alternatives for consideration and information on the environmental performance of these alternatives in terms of both LCI and LCIA indicators. However, the work extends that of Notten by framing the decision problem explicitly based on MCDA, which enables the consideration of financial and social aspects in addition to environmental aspects.

3.2 The Alternatives for Consideration

Notten proposed that the PF and FBC systems for consideration be defined by selecting particular combination of design variable choices and operating conditions, rather than attempting to evaluate all possible designs and operating conditions, or defining a discrete set of alternatives for consideration based on variations of a base case design. Notten defined three design scenarios per technology type in such a manner that they spanned extremes in environmental performance. These corresponded roughly to particular levels of refurbishment of the decommissioned power station. (See Notten [2001] for details regarding the definition of the design scenarios.)

3.3 The Evaluation Criteria and Performance Indicators

The aspects of concern to the company and to stakeholders that would inform the choice of preferred technology (i.e. the evaluation criteria) could be described broadly as financial, technical, environmental and social. The alternatives were designed to meet all technical requirements and indicators typically used by the company when considering the financial and social performance of designs were selected for the evaluation of the design scenarios. To allow for the comprehensive consideration of the environmental impacts of the technologies, Eco-Indicator 99 Hierarchist Perspective Life Cycle Impact Assessment (LCIA) indicators considered relevant to the decision context were selected (see Notten [2001] for details). Furthermore, to reflect specific concerns of relevance to the particular decision situation, two additional indicators were selected. These were an indicator for water consumption (considered important in the water scarce location of the decommissioned power station) and the affected land footprint (ALF) indicator developed by Hansen [2004], which provides a more comprehensive approach to the consideration of the impacts of solid wastes than the standard LCIA approach. The choice of evaluation criteria and the choice of specific performance indicators introduce valuation uncertainties into the decision process. The implications of such valuation uncertainties for decision making needed to be examined through sensitivity analysis (see section 3.7 later).

3.4 Data Collection and Enumeration of the Environmental Performance Scores

The environmental performance information was obtained using life cycle models (described in detail by Notten) and included information on the uncertainty in the inventory information based on the systematic evaluation of uncertainty associated with empirical parameters, model parameters and model structure. The values of the Eco-Indicator 99 LCIA indicators included the uncertainty in the equivalency factors used to calculate the impact potentials, which were available for most of the selected impact categories. Where such information was not present, estimates for the distributions of the characterisation factors were based on the work of Meier [1997]. To assist in the interpretation and preference modelling, the environmental performance information was normalised relative to average company performance for coal-based power generation. Uncertainty due to the variation in installed technologies and uncertainties associated with

modelling the company's operation were included in the estimate of the average performance.

3.5 Distinguishability Analysis

The normalised performance scores were subjected to distinguishability analysis via both PCA and the DI approach. The PCA results can be summarised by way of PCA biplots. This is illustrated in Figure 1 for the criteria set where the environmental aspects were assessed in terms of the Eco-Indicator 99 impact level environmental criteria and the additional criteria reflecting local concerns.

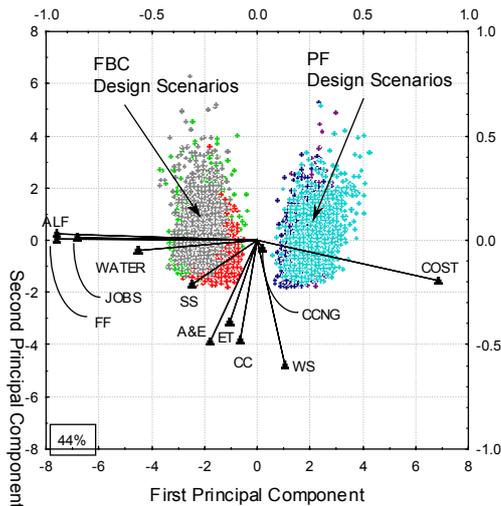


Figure 1 PCA biplot for the normalised performance scores

Codes: COST = Generating cost, JOBS = number of permanent jobs created, CCNG = carcinogenic effects on humans, SS = respiratory effects on humans caused by organic substances (summer smog), WS = respiratory effects on humans caused by inorganic substances (winter smog), CC = climate change, ET = ecotoxic emissions, A&E = combined effect of acidification and eutrophication, LO = land occupation, FF = extraction of fossil fuels, WATER = water use, ALF = affected land footprint

In Figure 1, the PF and FBC design scenarios form separate clusters, but the individual design scenarios overlap. This suggests that the technologies, but not the individual design scenarios, may be distinguishable from one another in at least some of the criteria. The arrows for the “principal factor loadings” associated with generating cost (COST), job creation (JOBS), fossil fuel consumption (FF) and the affected land footprint (ALF) are the longest and show the greatest correspondence to the axis representing the first principal component. This suggests that the two technology types differ most in these aspects. Furthermore, the principal factor loadings associated with generating cost and those associated with other three criteria lie almost diametrically opposite. The placement of the principal component scores for the two technologies suggests that the PF design scenarios perform better with regard to generating costs, while the FBC design scenarios perform better in terms of resource use and job creation. The key

trade-offs to be considered for technology selection are expected to be between performance in generating cost and performance with regard to fossil fuel consumption, impacts on land (as represented by the AFL indicator) and job creation.

To verify the extent of distinguishability between the design scenarios, the DI approach was applied (results not shown). The DI results confirmed that the two technology types were distinguishable from one another with regard to generating cost, fossil fuel consumption, the ALF and job creation, but showed that the performance scores in the other criteria overlapped due to the uncertainty in the performance information. In general, it would thus have been recommended that an attempt be made to reduce the uncertainty in the performance information before commencing with the detailed modelling of preferences with the view to selecting a preferred technology type. However, in this particular case the uncertainty in the performance information was considered to be associated with empirical parameters (see Notten for details), and could thus be described in terms of probability distributions. The uncertainty in the performance information could therefore be propagated through the analysis and some indication obtained of the relative ranking of the design scenarios in full cognisance of the implications of the uncertainties in the performance information.

3.6 Evaluation of Design Scenarios Using Value Functions Analysis

The performance of the design scenarios considering all the financial, environmental and social performance indicators was compared using value function analysis. A weighted additive aggregation function was used to create an overall value score to reflect the relative preference for the different design scenarios. Valuation uncertainties were thus introduced during this stage of the decision process through the choice of model forms for the intra-criterion preference models (i.e. shapes of value functions) and the choice of model parameters for the inter-criterion preference models, (i.e. values for the weights).

3.7 Sensitivity Analyses

To determine the sensitivity of the ranking of the design scenarios to the valuation uncertainties introduced during the decision process (highlighted in sections 3.3 and 3.6), it was necessary to conduct several parallel evaluations of the design scenarios. Furthermore, by propagating the technical uncertainties (i.e. uncertainties associated with the performance information) through these

parallel evaluations using a random sampling technique, it was possible to consider the implications for decision making of technical and valuation uncertainties simultaneously. The integrated approach for the consideration of technical and valuation uncertainties is demonstrated here by considering the evaluation of the design scenarios

- with and without the environmental criteria reflecting local concerns (sensitivity analysis for choice of evaluation criteria)
- using environmental indicators at inventory, impact (midpoint) and damage (endpoint) levels (sensitivity analysis for choice of performance indicators)
- using a combination of value function shapes and weights that place emphasis on good performance in environmental aspects and another combination that places emphasis on good performance in financial aspects (sensitivity analysis for intra- and inter-criterion preference models).

3.8 Results and Discussion

The overall ranking of the design scenarios, including the uncertainty associated these rankings, could be observed by plotting cumulative distribution functions for the overall value scores. This is illustrated in Figure 2 and Figure 3 for the value scores obtained using the criteria set illustrated in section 3.5 (Figure 1). Note that in Figure 2 and Figure 3 design scenarios with higher overall value scores are preferred to ones with lower value scores. The codes ER and SR correspond to “expected level” and “significant level” of refurbishment, respectively.

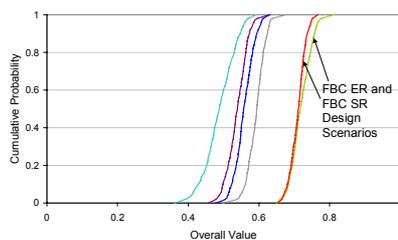


Figure 2 Overall value scores where emphasis is placed on good environmental performance

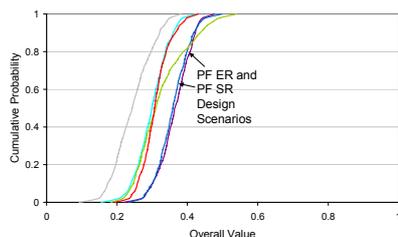


Figure 3 Overall value scores where emphasis is placed on good financial performance

Figure 2 and Figure 3 show that there is substantial overlap in the overall value scores of the design options. This is due to the uncertainty in the performance scores propagated through the analysis. However, despite this, it can be observed that when greater emphasis is placed on performance in environmental criteria, the FBC ER and FBC SR design scenarios are likely to be the preferred design scenarios (see Figure 2). If greater emphasis is placed on performance in the economic criterion, then the PF ER and PF SR design scenarios tend to perform better than the FBC design scenarios, but clear preference can not be established due to the uncertainty in the performance information (see Figure 3).

The rankings of the design scenarios are compared in Figure 4 and Figure 5, which present the principal factor loadings for the ranks of the design scenarios. Figure 4 compares the ranking of the alternatives with and without the additional environmental indicators, while Figure 5 considers the rankings for evaluations where the environmental criteria are represented by the Eco-Indicator 99 inventory (INV), impact (IMP) and damage (DAM) level indicators.

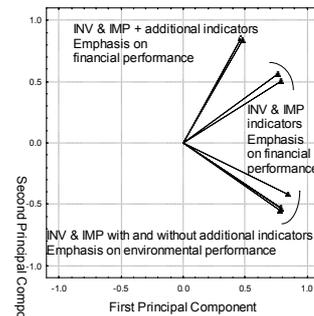


Figure 4 Principal factor loadings for the ranking of the design scenarios with and without the additional environmental indicators

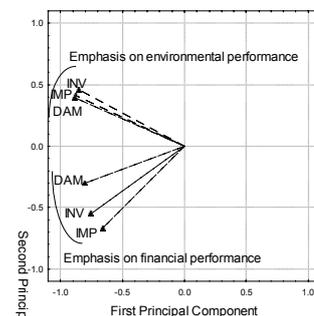


Figure 5 Principal factor loadings for ranking of the alternatives (environmental criteria represented by Eco-Indicator 99 inventory (INV), impact (IMP) and damage (DAM) level indicators)

The relative positions of the arrows representing the principal factor loadings of the ranks of the

design scenarios for the parallel evaluations indicate that the relative preference of the design scenarios was sensitive to the valuation uncertainties associated with the choice of criteria (i.e. inclusion and exclusion of environmental criteria reflecting local concerns, Figure 4) and to the choice of the position of the indicators in the cause-effect network (assessment of environmental performance using inventory, impact and damage level indicators, Figure 5). However, in both cases, choices made during intra- and inter-criterion preference modelling had a more significant effect on the ranking of the design scenarios. For the case study decision, the results suggested that stakeholder involvement in intra- and inter-criterion preference modelling was essential.

4. GENERAL CONCLUSIONS

When making decisions it is necessary to ensure that the alternatives selected for further consideration/implementation are consistent with the value systems and preferences of the stakeholders. This requires the explicit modelling of stakeholder values and preferences rather than “encoding” of value judgements and preferences in the information used to support decision making. The latter may well be the effect of a call for greater standardisation of LCA methodology and a drive towards endpoint modelling which denies stakeholder an opportunity to explore their values and preferences and examined the effects of these on the decisions to be made. As a whole, this provides support for a call for diversity in LCA methodology rather than one for greater standardisation. The approach for the consideration of uncertainty presented in this paper provides a foundation for the consideration of the implications of such methodological diversity as part of an overall approach to promote effective decision making based on LCA environmental performance information.

5. ACKNOWLEDGEMENTS

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