

Perceptual Scaling in Materials Selection for Concurrent Design

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Abstract

In this short paper, we describe the development of an adaptive design assistant to support and advise design team members when selecting materials for manufacture. Candidate proposals for materials are identified when the user subjectively rescales a similarity-based representation of materials. The approach taken seeks to acknowledge that personal decisions do not always appear rational and to address some of the often ignored problems that are encountered when scaling, clustering and categorisation are performed using a large number of highly correlated attributes. A short illustration of the approach is included.

Introduction

We are interested in understanding the psychological processes by which designers identify alternative design proposals during collaborative design negotiation. Of particular interest are design proposals that are perceived to be novel or innovative. Our goal is the development of an Adaptive Design Assistant for Materials (ADAM) to support and advise design team members when selecting materials, mainly for parts, and packaging.

The functionality of ADAM is modelled following an exploration of the way in which individual designers dynamically restructure a similarity-based multidimensional representation of materials as their perception of the current design problem changes e.g., through negotiation and discussion. This process generates a set of design proposals that can be privately evaluated and offered in negotiation (Barker, Holloway and Meehan 2001a). The process of dynamic restructuring may result in individual materials being reassigned to new and different clusters or categories. Sometimes the reassignment is puzzling or unexpected and in such cases, we suggest, they may be perceived as novel or innovative.

An important aspect of the work we describe is that our concern is to capture as closely as possible the way in which an individual designer categorises materials they work with and encounter. We seek to discover the rational underpinning of categorisation or decision making by designers: we attempt to avoid imposing a rational

framework *ab initio*. Accordingly, we fully anticipate that a designer's perspective on materials selection may be inconsistent with standard rational models. We take the view that during negotiation people's choices will change precisely because their views do depend on the framing of the problem (description dependence), the method of evaluation (procedure dependence) and the context of the choice (frame dependence). In this respect, we share the opinion of Tversky (1996) in which it is proposed that models of decision makers should accommodate decisions based on seemingly irrational inferences.

The remainder of this paper first looks at a model of the collaborative design process that informs the design of ADAM. It summarises an 'objective' representation of materials based upon published literature (Holloway 1998). It then argues that designers do not share this representation, maintaining, instead, their own subjective representations and outlines a knowledge model for ADAM that is informed by these considerations. The model is demonstrated by means of an example. Finally, we make some comments on the work undertaken and outline our current line of investigation.

The Design Context

Design is an important economic activity and many computer-based systems have been developed to support design work. Design activity is organised in many ways. Concurrent design is one particular approach that seeks to incorporate a number of different product life-cycle perspectives (so-called 'downstream' perspectives) at the product design stage. Downstream perspectives commonly include manufacturing, assembly, maintenance and marketing. More recently, anticipated changes in legislation and consumer attitudes have introduced the perspective of environmental impact. (There is relatively little expertise in this area and this provides another motive for the development of ADAM.) Incorporation of these perspectives at the earliest stages of design aims to minimise the number of (expensive) revisions that are triggered if faults or non-optimal solutions are detected only at a much later stage.

Barker, Meehan and Tranter (1999) offer a knowledge-model of the concurrent design process. The model is iterative and features three high-level processes; *propose*,

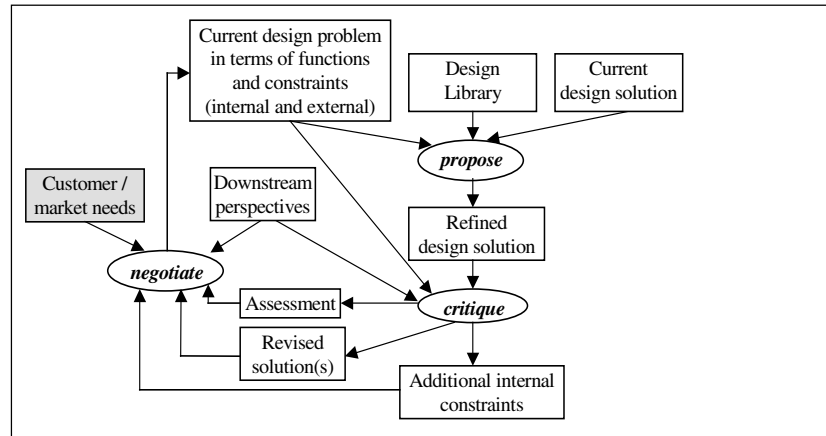


Figure 1. Knowledge model for concurrent design. The process *propose* draws upon a current working solution to generate a refined design solution that is then subject to the processes *critique* and *negotiate* (Barker, Meehan and Tranter 1999). The focus of this paper is the negotiation of materials for manufacture which draws upon downstream perspectives such as product assembly, maintenance reuse and reprocessing.

critique and *negotiate* (Figure 1). In keeping with many other models of design, it takes the view that, especially in the later stages of design, designers propose refinements to a current working solution. It has been observed that Designers use the concept of *similarity* (in relation to the current design solution) when selecting a new proposal for negotiation (Barker, Holloway and Meehan 2001a). In the context of collaborative negotiation, given a set of alternative proposals that might be made, the proposal that is most similar to the currently agreed working solution is more likely to be accepted by others in the team. This form of behaviour reinforces team effectiveness (Pruitt 1981). In developing ADAM, we have chosen to try to capture this strategy for identifying alternative proposals.

‘Objective and ‘Subjective’ Representations of Materials

Materials can be represented in a multidimensional space whose dimensions are the ‘objective’ attributes or properties that they possess. In this instance, we view as ‘objective’ the materials related data that is published by accredited bodies responsible for materials analysis and standards. There would be clear advantages to using such data in the implementation of ADAM, not least of which would be the significant reduction in the work required to develop and maintain a materials knowledge-base. Unfortunately, (and unsurprisingly) it has been demonstrated that designers do not share such an objective view of materials (Barker, Holloway and Meehan 2001a). This implies the need for some form of

mapping between an objective (public) and a subjective (private) representation for each designer.

Holloway (1997) has analysed the attributes of materials that appear of relevance to designers holding different roles within a concurrent design team. This analysis spans over 50 classes and sub-classes of materials and reveals a large number of attributes for which published values are presented in the materials literature. The different design perspectives documented include materials analysis (162 attributes), mechanical properties analysis (22 attributes), production processing (25 attributes) and environmental impact analysis (53 attributes). Not only do these different perspectives not share a dimensional framework for materials; personal categorisations are shaped by the subjective value designers attach to different dimensions.

As indicated above, in order to exploit a universal ‘objective’ representation of materials, it is necessary, when personalising an ADAM, to find a mapping between the ‘objective’ and the ‘subjective’. Although a number of approaches to obtaining this mapping might suggest themselves, in practice, it is not a trivial task for at least two reasons. First, many of the ‘natural’ attributes of materials are highly correlated. Second, the large number of dimensions used by each of the designers’ perspectives greatly diminishes the feasibility of any approach that requires the direct elicitation of weights or scaling factors. In the next section, we describe an implementation of ADAM that is facilitated by an approach that uses a greatly reduced set of independent dimensions.

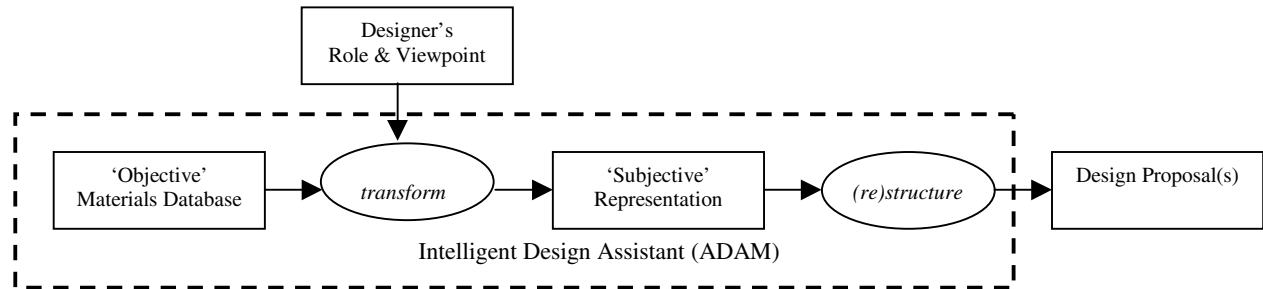


Figure 2. Each designer's ADAM takes an expression of its user's viewpoint and transforms a standard materials database into a subjective representational space. Structuring and restructuring of materials within this space is used as the basis for identifying alternative design proposals. The functionality bounded by the dashed line represents an expansion of the process *negotiate* in Fig. 1. Designer's Role & Viewpoint corresponds to the Downstream Perspective in Fig.1.

Knowledge Model for ADAM

The above scheme suggests the following model for an ADAM (Figure 2). An example will be used to illustrate the implementation. The components of the model are:

'Objective' Materials Database: each ADAM shares a database of materials gleaned from data published by sources responsible for analyses and materials standards. The attributes of the database are not independent of each other. The database is easily represented as a single relational table. (The database is maintained from published sources. At present this is done manually.)

Designer's Role & Viewpoint: each user defines their role and viewpoint (e.g., materials analyst, process engineer, environmental impact analyst) and contributes a subjective assessment of the importance of the different dimensions they use to represent materials. We choose to rank subsets of attributes as the means of expressing this subjective weighting. (See *transform*, below, for an account of how the subset of attributes is selected and presented).

Subjective Representation: a representation of materials that reflects the user's personal perspective. This is a transformation of the 'objective' materials database. The transformation uses subjectively re-scaled rotated principal components in order to achieve a mapping from the 'objective' database to a subjective, dimensionally reduced, representation of materials for its user (see *transform*, below).

Design Proposal(s): set of suggested alternative materials.

***transform*:** maps the 'objective' database to the 'subjective', user specific representation of materials. As indicated above, the transformation uses re-scaled rotated principal components (RPC). The RPC-based transformation is achieved as follows:

***Standardisation*:** the units of the different natural attributes are not comparable and so standardised scores for the original values are used;

***Dimension reduction*:** the method of principal components is a well-understood approach to achieving a more parsimonious representation of a multidimensional space. Rotated principal components is a modification of the technique that maintains a set of orthogonal components whilst offering a more accessible association between natural dimensions and rotated principal components. This makes it easier to explain to designers why some natural dimensions are of greater interest than others when eliciting rankings at a later stage (see re-scaling, below).

***Re-scaling*:** the user is invited to rank those natural attributes that dominate the rotated principal components. This ranking is then used to re-scale the principal components space to reflect weight that the user attaches to these significant attributes.

***(re)structure*:** this process clusters materials based on *similarity* to identify alternative materials that are considered similar to the current design solution. On the basis of the rankings of natural dimensions (e.g., 3,2,1), the scaling of components is varied. The restructuring recategorises some materials in ways that are not entirely intuitive, but are nonetheless of interest as novel proposals.

Example

This example is designed to illustrate the above scheme. The design perspective chosen is that of environmental impact analysis. The example is constructed using a sample of 21 materials represented using just six sample dimensions (Table 1) chosen randomly from the full database.

Table 1. Labels used for sample dimensions of materials.

Label	Description
BOD	Biological Oxygen Demand
OILaq	Oils discharged to water
COa	Carbon monoxide discharged to atmosphere
HydroCa	Hydrocarbons discharged to atmosphere
NOa	Oxides of nitrogen discharged to atmosphere
DSaq	Dissolved solids discharged to water

Just two principal components account for nearly 78% of the variance in the set of 21 materials considered (Table 2). For the purposes of this example, we will work with two principal components.

Table 2. Principal components analysis of a sample of 21 materials on a sample of 6 standardised dimensions (BOD, COa, NOa, HydroCa, OILaq and DSaq). Just two components account for nearly 78% of the variance from the sample.

Component	Initial Eigenvalues		
	Total	% of Variance	Cumulative
1	2.547	42.446	42.446
2	2.122	35.372	77.817
3	0.882	14.704	92.552
4	0.243	4.043	96.564
5	0.154	2.570	99.134
6	0.052	.866	100.000

Table 3 gives the coefficients associated with each of the 6 natural dimensions in contributing to the non-rotated and rotated principal components. It shows how each of the rotated components are more clearly associated with a subset of the natural components (e.g., note the change in the coefficients of OILaq.)

Table 3. Non-rotated and Rotated Component matrices for two extracted principal components. (Uses Varimax rotation with Kaiser normalisation). The rotation results in a clearer association between principal components and natural dimensions; BOD, COa and NOa with component 1 and Hydrocarbons and OILaq with component 2.

	Non-rotated Components		Rotated Components	
	1	2	1	2
BOD	0.945	0.037	0.933	-0.155
COa	0.892	0.382	0.951	0.193
NOa	0.810	0.136	0.821	-0.030
HydroCa	-0.190	0.855	-0.010	0.875
DSaq	-0.030	-0.707	-0.173	-0.686
OILaq	-0.406	0.852	-0.225	0.916

We exploit this clearer association of components with dimensions to facilitate the scaling of the components by the designer. The natural dimensions are grouped on the basis of their association with the rotated components and ask the designer to rank these groups. For small groups, this is not difficult.

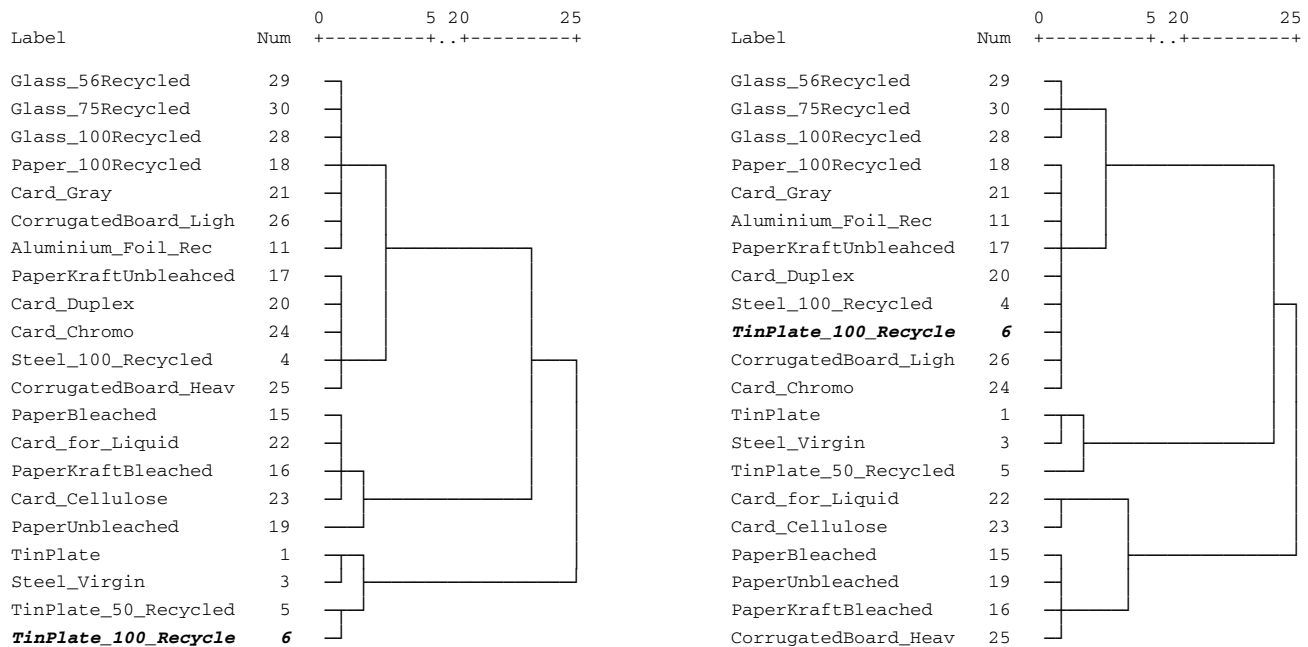
As mentioned above, we have begun to look at the effect of different scalings of the components. In our first experiments, we have used a scaling that ranges from the root of the allocated scale factor to its square. These modest variations in the subjective scaling may result in the recategorisation of some of the materials. The effect is readily visualised by comparing two (or more) dendrograms. Figure 3 shows two such categorisations resulting from two different scalings. This recategorisation illustrates how changes in subjective scaling of some dimensions results in the recategorisation of a previously somewhat distant solution or proposal (e.g., material 6).

Discussion

The aim of this exploration is to better understand how designers generate alternative design solutions during negotiation with a view to developing a design assistant (ADAM) that can advise or eventually act for individual designers. The example above illustrates the method we have used to examine how, as a result of discussion and negotiation, subjective rescaling of a similarity-based categorisation of materials by an individual designer may lead to recategorisation and the identification of alternative, sometimes unexpected, solutions.

There is clearly much more to explore. The least understood step in the scheme is how to select the natural dimensions to be used as stimuli for the designers when eliciting scalings which will be applied to the (rotated)

Figure 3. Dendrograms to illustrate the effect of subjective rescaling of rotated principal components representation of a set of 21 materials. 100%-recycled tin plate is highlighted as a material that has experienced a significant recategorisation.



principal components. One possibility is to identify those dimensions which designer believes to be causally related as opposed to those which are believed to have a non-causal correlative relationship. Implication grids could assist this identification.

The current range over which a single scaling factor is allowed to vary is relatively arbitrary and it may be of value to explore sensible, possibly individualised, ranges for the different users.

The effect of different similarity measures may also need to be considered. Initial investigation with Minkovski distances suggests that the categorisation is insensitive for values of $r \geq 2$. There is a minor recategorisation when $r=1$. With a suitable visualisation technique, it is possible to image the results of rescaling resulting in a system that allowed interactive exploration of cluster/category formation.

Acknowledgement

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