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THE EFFECTIVENESS OF PSYCHOLOGICAL DISTANCE IN AN EMPIRICAL STUDY OF GUIDELINE CLUSTERING FOR AEROSPACE DESIGN

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Abstract

This work continues development and evaluation of a practical approach to a Design Research Methodology developed previously [1] and extended to practical application in [2] and concentrates on new empirical techniques for research evaluation. The methodological challenge was to seek, without preconceptions, a research approach that enabled insight into the unobservable organisation of designers' knowledge of guideline content. A number of designers' perceptions of the similarity between items in a collection of aerospace guidelines were collected using a triad comparison. An analysis was developed that combines non-metric multidimensional scaling analysis with hierarchical cluster analysis in order to represent the inherent structure of the perceived similarity in this data. This structure was established by examining the groupings and linear dimensions formed in the analysis outputs and relating these to guideline content. The results, which are not directly related to the standard engineering guideline organisation, may be a new indication of designers' mental models; suggesting that perceived similarity ratings and the analysis methods we have developed could be a powerful tool in eliciting designers' knowledge in general.

Keywords: information structuring, design guidelines, cluster analysis, similarity scaling

1. Background and Objectives

Conventional observation studies used in design research collect a corpus of interview or protocol data and infer qualitative and quantitative relationships between design elements on the basis of tacit process hypotheses or design theories. An alternative approach is to represent operationally design information and empirically examine the way in which designers' cognitively organise the presented information. Such a descriptive study of complex data is conventional in social sciences and archaeology but rarely used in design research investigations. As cognitive maps of design information are unobservables that exist only in the minds of designers, they can only be inferred from the relationships between elements that they are asked to relate. In particular, the concept of *perceived similarity* as psychological distance between multi-featured information elements can be used to infer the mapping of groups, clusters or dimensions of related design knowledge. The purpose of the reported methodological approach was to trial a number of alternative approaches to revealing cognitive maps of designers' understanding of their working domains. This was achieved by using techniques derived from psychology that map individuals' perceived ratings of similarity between presented objects to general cognitive maps.

1.1 Practical Design Research Methodology

A majority of design research, to date, has focused on developing, and in some cases testing, new design methods. Little of this research has adopted a rigorous research methodology, which is not surprising, bearing in mind the complexity of the engineering design process and hence design research. The practical approach taken here is based on design research methodology developed by Blessing, Chakrabarti and Wallace [1] with particular emphasis on practical empirical evaluation. In the first stage, *Criteria formulation,* measurable criteria are identified, such as "reduced time to search" together with a network of causal influences linking back to success criteria such as "increased profit". The second stage, *Descriptive Study I,* analyses the existing design process or product aiming to discover relations between the measurable criteria and the design process or product to identify where application of a design method could lead to improvements. In the third stage, *Prescriptive Study,* insights gained in *Descriptive Study I* are used to create an intervention for an improved design process that could result from using the new design support. This intervention creates a starting point for specifying and implementing design support. Finally in *Descriptive Study II* the design support is tested experimentally to determine whether it works as intended and whether it actually impacts the measurable and thereby the success criteria. The approach aims to give information on the applicability and use of methods involved in experimental design, analysis, data collection or presentation. Empirical methods can be applied at the descriptive level of the methodology or at the evaluative stage. The aim of the next stage is to further develop, evaluate and disseminate the framework for an integrated methodology for Engineering Design Research within the context of industrial engineering design. We aim to analyse the methodology of specific case-study projects in real design situations, focusing specifically on integrating the use of experimental and empirical techniques. This will also enable a methodical assessment of the practical use of design research methods, in general, and the development of guidelines for a practical integrated methodology that can be applied to industrially linked problems.

2 The Perceived Similarity of Guidelines Case-study

The methodological case-study was carried out in conjunction with continuing research into knowledge capture and reuse in the context of engineering design projects in a real industrial context [3, 4, 5]. Guidelines for use during aerospace design are conventionally organised and indexed according to in-house design process classifications or using standard engineering ontologies. However, the structure imposed on information may cause navigational confusion or act to impede the retrieval of information if it is not aligned with a particular search parameters or an individual designer's understanding of a design issue. The general aim of this study is to try to establish the designers' cognitive maps or conceptualisation of a guideline space in order to generate alternative organisations that may lead to faster and more efficient searches. The scaling of rated distances between elements can likewise be used to establish the structure of designers' knowledge space by identifying dimensions of relatedness between groups of knowledge elements. Two commonly used data exploration methods from the social sciences are well suited to these approaches: Hierarchical, agglomerative Cluster Analysis [6] and Non-metric, Multi-Dimensional Scaling (MDS)[7]. In principle, once the perceived similarity between guidelines are established by means of direct juxtaposition or ranking techniques, iterative algorithms may be applied to attempt to fit them into spaces with varying numbers of dimensions. If the data is not randomly and homogenously distributed, "true" dimensionality and natural clustering can be ascertained from numerical estimates of the difficulty of fitting the data to a specific dimensional interpretation. Hence, one possible outcome is that the objects do not form any cohesive clusters or lie on any identifiable dimensions that can be related to the engineering content. The alternative is that such dimensions or clustering can be identified and that they are common to a number of designers rather than specific to each individual. However, in order for this approach to be adopted, it is assumed that the mathematical properties of the space into which the similarity ratings can be "fit" is regular. This is to say, that it is assumed that psychological spaces are approximated by "metric" spaces with particular mathematical properties. Non-metric multi-dimensional scaling is a data exploration technique designed specifically for similarity judgement data [8].

2.1 Metric assumptions

The designers provide a subjective similarity ranking, between objects, for example they may be asked for a number between zero and twenty. If this value is taken as a proximity or distance estimate it can be mapped into a metric space. For example, it is possible to map points into a 2D Euclidian space, based around conventional geometry. A number of metric assumptions are made. The first is that the distance between a point and itself is zero. The second is that the distance between two points would be equal to the measured inverse distance (i.e. distance *ab* = *ba*). The third assumption is that of Triangle Inequality, for example, that the hypotenuse of a right-angled triangle in the space is longer than either of the two other sides. These assumptions are used by both MDS and clustering techniques [6. 7]. The effect of rescaling distances into metric space is that it reduces the complete set of distances to $n (n - 1) / 2$. Metric spaces may have multiple dimensionalities. For example, 2D or 3D Euclidian spaces are familiar but higher dimensionality Minkowski metrics are possible.

2.2 The Pilot study

A pilot study was carried out to test the capability of data exploration techniques for the classification of guideline text segments according to pair wise ratings of distance. Working designers from an aerospace design environment were required to rate the similarity between a set of design guidelines presented in all combination pairs. An advantage of this approach was that only a single question, *how similar is guideline a to b*, need be asked in order to form a map of how engineers structure knowledge. In this exercise, pairs of design guidelines are presented to an engineer. After MDS re-scaling of the distances, the relationships between guidelines expressed as co-ordinates in the chosen dimensional space were analysed in terms of proximity using hierarchical cluster analysis. The resulting clustering were visualised in projection where possible and the engineering relationships between closely grouped guidelines ascertained.

The designers' distance judgements were found to scale well into 3 dimensional space as confirmed by stress level analysis. Furthermore, the metric scaling facilitated the cluster analysis that yielded three principal clustering of guidelines as indicated by an analysis of cluster formation distances. The results suggest that guidelines were grouped into three areas: those to do with: (1) design stress (2) dimensional considerations (3) General manufacturing. Preliminary analysis suggested a high degree of agreement between designers in their judgements. The level of between-designer agreement and analysis of the group scaling dimensional solutions was calculated using the INDSCAL approach of Kruskal [7]. The results suggested that the majority of designers' shared formed a group with highly related conceptualisation of the guidelines segments while a number of designers had idiosyncratic interpretations. This success of the pilot suggested that the same methods might be applied to aerospace guidelines in the primary study.

3 Methods

3.1 Obtaining Similarity Data

Obtaining ratings of similarity directly from people is a technique based on psychological scaling approaches. Here, as when someone is asked to order coloured cards in order of "redness" or weight, it is assumed that the individual makes the judgement according to internal cognitive organisation about which they may have no insight [8]. For this reason, individuals may have no difficulty assigning distances between objects when there often is no apparent basis to do so. It is important, therefore, not to instruct designers on how to make their judgements, as to do so would bias their performance in favour of some preconception on the part of the researcher. This was the approach taken in these studies. As in psychological scaling, a variety of methods may be used. Objects may be presented in pairs and similarity reported as a number or marked on a physical scale. Alternatively, items may be laid out or ranked according to their order of difference from a standard, or pairs of greater similarity selected from presented triads. This study relies upon similarity ranking of engineering guidelines to provide a measure of the cognitive distances between different pieces of engineering knowledge. To determine the constructs used by engineers to structure knowledge, a similarity ranking exercise based on Personal Construct Theory [9, 10] was used.

3.2 Personal Construct theory approaches

Although not used as a basis for interpreting the data, Personal Construct Theory (PCT) [9] provides a basis for collecting similarities. In the theory, each individual is assumed to build a series of constructs by which they interpret the world around them. These constructs may be measured and give an indication as to how an individual understands their world. Typically, repertory grids are used to collect relational information in a two-step process. Triplets of objects are presented and the subject required to choose two that seem closest. They are then asked to identify the basis for that decision and made to scale all the remaining objects on their own new scale. A similar approach to the triadic construct approach used in PCT was utilised to obtain similarity ratings in the present studies and also to force the designers to generate constructs that could be used to interpret the data.

3.3 Sampling

A crucial aim was to ensure the accuracy with which the research represented the true nature of the conceptualisation of the design guidelines. Due to time and fatigue constraints, only a sub-set of the data could be presented to designers. Hence, a random sub set was generated, of sufficiently large size that even sampling of the guidelines set was made across all individuals. Eight engineers were presented with sub-sets of 75 guidelines concerning wing fuel-tank design.

3.4 MDS

Metric and Non-metric MDS were then used to ascertain the dimensionality that best suited the obtained distance matrix, obtained through a process of minimising numerical stress (a measure approximating goodness-of-fit). This procedure also converted non-metric psychological distances (those that could not be represented in a mathematical metric space such as that described by a Minkowski metric) into metric distances suitable for input into a cluster analysis. The raw similarity data formed a non-metric set of distances defining the relative positions of the guidelines in a space of n-1 dimensions. The matrices were processed and combined to a single solution using non-metric MDS (Proxscal) in SPSS. The data was then scaled to two, three, four, and five dimensions. This is the valid range for this data set [7]. The stress values were then plotted against the number of dimensions. In MDS, stress is a measure of the amount of numerical distortion that occurs when a set of points is fitted to specific number of dimensions. Figure 1, displays the typical progression of decreasing stress as the number of dimensions increase for the pilot data. The number of dimensions to use is based on a selection from the point on the curve where the highest change of slope occurs [7]. In the present study, this corresponded to three or four dimensions.

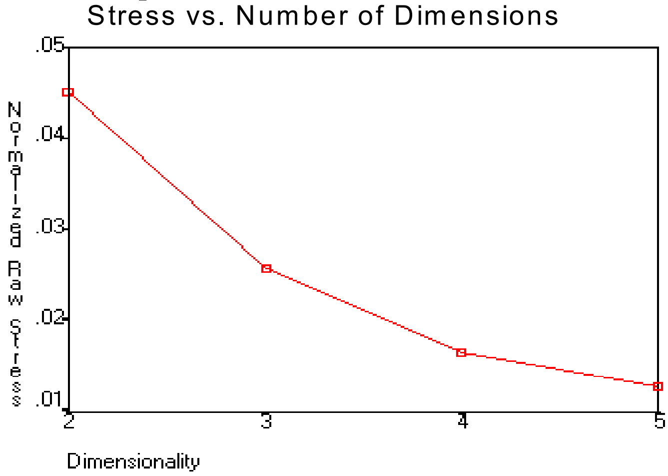

Figure 3. Decreasing stress with increasing dimensionality

For the data obtained from the main study, several steps were taken in the data processing to combine the data to create a common set of guideline similarity distances for analysis. The inter-point distances were first calculated. This resulted in a 40 x 40 dissimilarity matrix (the numerical inverse of a similarity matrix). These distance values were then combined by averaging the individual distance values to the appropriate location in a 75 x 75 matrix representing the entire guideline set. The resulting non-metric space was scaled to both two and three dimensions using the Proxscal variant of MDS in SPSS. An *ordinal* proximity transformation model was chosen. The resulting data was then clustered using the *centroid* method. There was no significant difference between the cluster patterns formed from either of these dimensions. In addition, the stress value at two dimensions was low enough (0.055) [6]. As a result, direct analysis of the conceptual space was done in two dimensions, but the use of three or four dimensions in dendrogram plots would have given a slightly more accurate depiction of the data. The 2D solution space for the full guideline set is shown in Figure 2. Although no clustering has taken place at this stage, it is clear that considerable grouping of the data has occurred. Cluster analysis was now employed to examine the grouping structure of the data.

3.5 Cluster Analysis

After MDS re-scaling of the distances, the relationships between guidelines expressed as co-ordinates in the chosen dimensional space were analysed in terms of proximity using hierarchical cluster analysis. A number of linkage methods known to possess linkage bias were examined for agreement in their clustering and a split-sample reliability studied carried out by clustering the data in two randomly chosen half-sets and confirming their agreement. Finally the number of clusters appropriate for the hierarchical dendrogram formed by the analysis was obtained by examining the plot of distance against cluster formation.

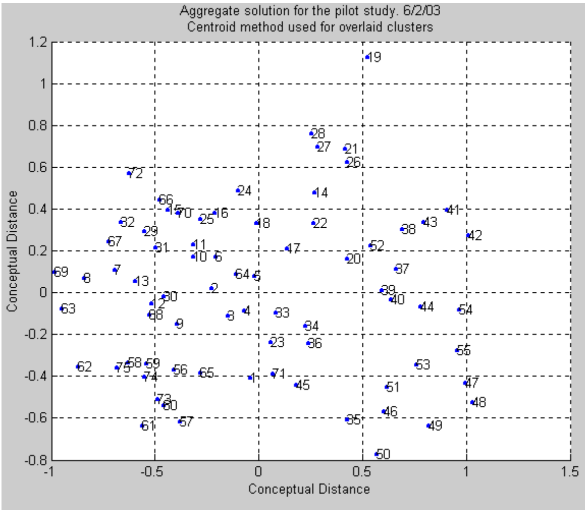

Figure 2. The 2D MDS solution for the Guideline data

Discontinuities and slope changes in this plot indicate regions of rapid cluster member joining and hence reflect the distance relationships between clusters. An example dendrogram from the pilot study shows how the clustering history is represented by a tree structure (Figure 3). The resulting clustering were visualised in projection where possible and the engineering relationships between closely grouped guidelines ascertained.

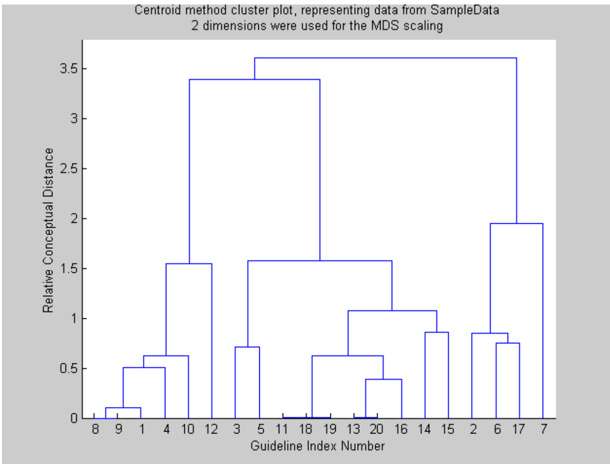

Figure 3. An example of a dendrogram from a sub-sample of data from the pilot

The use of the dendrogram allows the microstructure of cluster formation to be traced. Figure 4, shows the clustering at low and high distance levels of the analysis superimposed on the 2D MDS space. This reflects the number of jointing between guidelines that can occur at small (left) and large (right) distances between candidates for cluster membership. This information was used to ascertain the sub-groups and their dimensional relationships at the next stage of analysis.

4 Analysis

In addition to groupings that could be described with reference to their membership and central members, it was also possible to identify possible dimensions of variation across both the major axes of clusters and across aligned cluster.

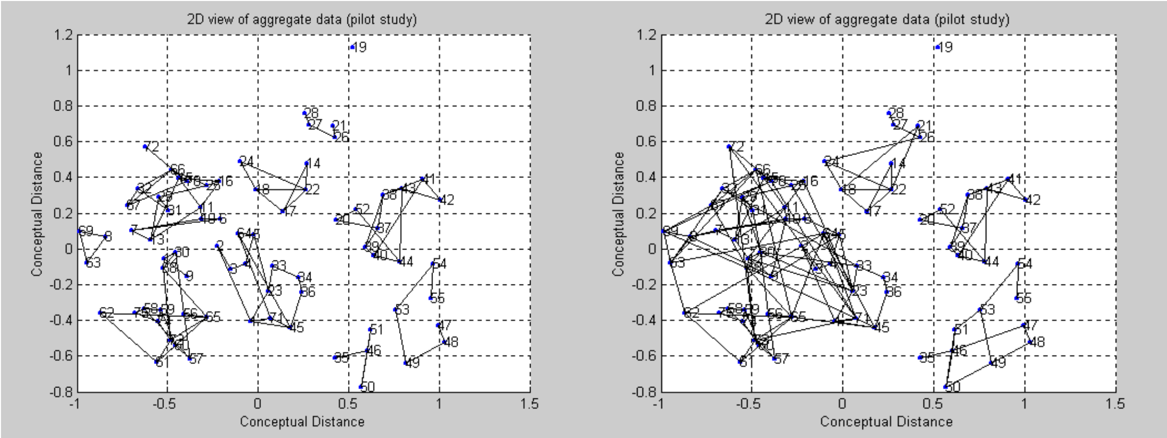

Figure 4. A low distance (left) and high distance (right) level clustering of the MDS data showing cluster membership by connecting lines.

This was achieved by examining the nature of guidelines along a major axis of a cluster and examining the relationships between the content of the guidelines for micro-clusters at the extremes of the axis. If a putative dimension was identified, attempts were made to verify or disconfirm it by examining other guidelines that lay at intermediary points, whose properties would be predicted by the dimension. The designers' distance judgements were found to scale well into 3 dimensional space, as confirmed by stress level analysis and this was used to confirm that the observed groupings were essentially 2D as well as to disambiguate cluster structure (Figure 5). Isolated guidelines playing little or no part in the pattern observed, such as guideline 19, were taken to be the result of MDS or clustering algorithm failures or the result of errors arising during the similarity scaling process. A number of guidelines were erroneously identical to others and these were verified as scaling close to their partners, confirming the robustness of the approach. After matching the guideline numbers to the corresponding design information, the concepts for each cluster became apparent.

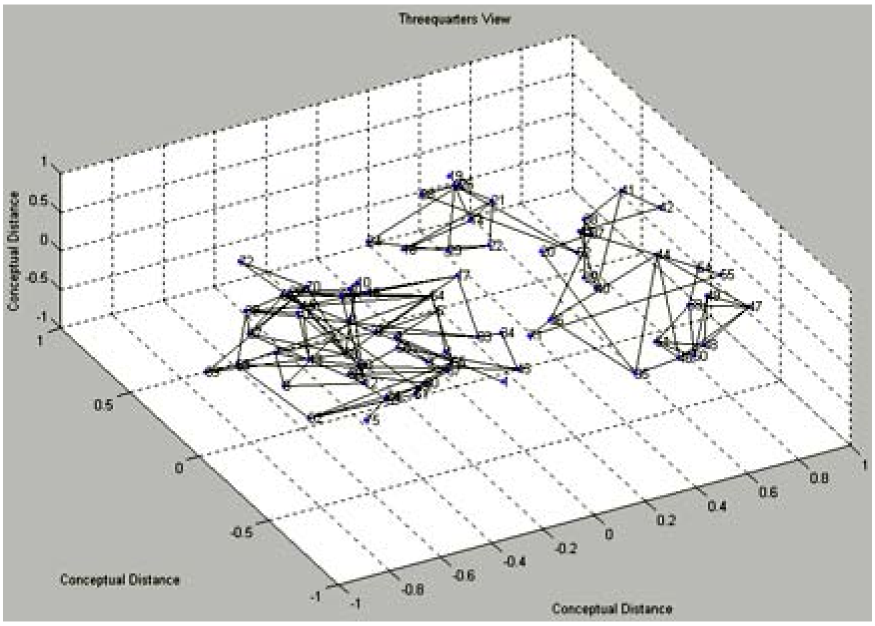

Figure 5. The 3D scaling solution for the clustered guidelines

Figure 6, Shows the revealed dimensionality superimposed on the MDS solution. The first cluster, **1** deals with the structural aspects and the components of fuel tanks, the second cluster, **2** generally pertains to sealants, and the third group, **3** is focused on electrical bonding.

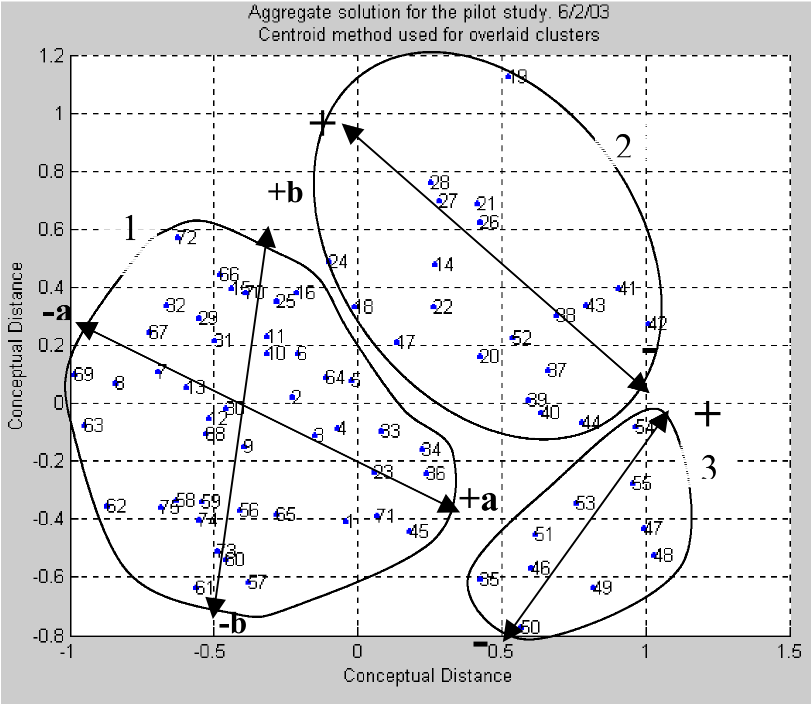

Figure 6. The dimensional cluster structure related to the cluster sub-structure

4.1 Dimension analysis

When the first cluster was subjected to further scrutiny, it was noted that there were two major axis of variation. While these axes are not orthogonal they appeared to adequately describe the conceptual space. The negative end of the *b* axis has guidelines about fuel pipe specifications and properties, such as pressure, material, routing and safety requirements. The positive end of this *b* axis has guidelines that relate to issues about the layout or construction of fuel tank boundaries. The midpoints on this axis (and the *a* axis) relate to fuel tank access. In defining conceptual similarity, this shows a dimensional progression of design concepts along the cluster, to do with fuel tank structure and components. The *a* axis in this group represents a dimension of concepts which shares a common point with the *b* axis. In addition, these conceptual axes accurately describe the location of the other guidelines in this cluster. These identified dimensions appeared to be well matched to cluster microstructure and related to identified guidelines in an intuitive way.

4.2 Alternative Approaches

One approach to organisation of guidelines would be the WEBSOM [11] whereby a Kohonen Self Organising Map is used to organise large databases of information. However, this method is dependent on the extraction of invariant features from the data archive, whereas the aim of this study is the elicitation and testing of the cognitive spaces of similarity obtained from the designers themselves. An alternative method of analysis would be the use of Kohonan Self Organising Maps [12] to represent the guideline relatedness space. Two ways in this might be achieved would be to apply a SOM to the psychological similarity data before MDS or after MDS. However, a distinguishing characteristic of psychological data is the possibility of it being non-metric. This is to say, that psychologically obtained distances from object rankings or perceived similarity scaling may violate metric assumptions. For example, the distance between two identical objects may be perceived to have a value rather than being zero, or the similarity between A and B may be different than the perceived similarity between B and A when judgements are mode. Since the Kohonen SOM's are based on metric assumptions and use Euclidian spaces, their behaviour with non-metric spaces is not well understood. The MDS approach was specifically designed for the re-scaling of such data and hence forms a more appropriate first stage of analysis. The SOM could be used at the post-MDS stage as a display tool, but it is not clear how the lattice representation would perform a useful role. In particular, the guidelines will no longer form identifiable points in the SOM space, which is an approximation interpolated form the original distance points.

A more interesting analysis might be carried out after the MDS and clustering stages outlined above. In this approach the data from the sub-clusters identified by the cluster analysis could be independently analysed. A particularly effective way to do this would be to employ Pricipal Component Analysis (PCA) to identify the primary axes of the cluster structures. A similar approach would involve the use of factor analysis to establish the guideline points that were accounting for the majority of variance along a particular dimension. Finally, multiple linear regression analysis could be used to establish the predominance of dimensional constructs used in the original triadic comparison stage. In this way additional information concerning the basis for grouping items of a triad could be used to suggest further cognitive relations between the guideline objects.

5 Validation

A validation of the resulting dimensions and groupings found using the combined methods employed, could be made by embedding them into an implementation of a search or information retrieval software or intranet tool. Such a tool might utilise hypertext guideline segments that may be retrieved in any order, or may present search options that reflect the psychological dimensions of the guidelines data. Alternatively, an indexing or search scheme based on the constructs, clustering and dimensions established by the approach described could be tested in an empirical test for improvement of speed and accuracy of search in comparisons with conventional provision. Finally, the effectiveness of the combined MDS/Clustering method may be evaluated by submitting the results to judgement by experienced aerospace designers for accuracy, relevance, usefulness and applicability.

6 Conclusions

This work consists of preliminary evaluation of the effectiveness of a practical methodology that integrates empirical methods from the social sciences and design research. We have successfully demonstrated the usefulness of the use of similarity judgements in conjunction with a multi-dimensional scaling approach combined with hierarchical agglomerative clustering of psychological distances between design guidelines. The findings reported represent promising initial findings using university engineers and graduate student representing designers and engineers. Further analysis will explore further constructs used in the triadic similarity collection method. The approach will be extended to include a more inclusive set of guidelines sourced from a large aerospace company and will be presented to a larger group of working designers for judgement.

Following the methodology adopted in [2] we will complete this work by evaluating the outcome of the use of the combined methods as measured by success criteria, discussing the applicability, advantages and disadvantages of the integrated method.

References

[1] Blessing, L. T. M., A. Chakrabarti and Wallace, K. (1998). An Overview of Descriptive Studies in Relation to a General Design Research Methodology. Frankenberger, P. Badke-Schaub and H. Birkhofer, Springer: 42-56.

[2] Langdon, P.M., Bracewell, R.H., Blessing, L.T.M., Wallace, K .M. and Clarkson, P.J., 2001, A practical methodology for Integrating software development and empirical techniques in design, Proceedings, 13th ICED., S. Culley, A. Duffy, C. McMahon and K. Wallace, eds. IMechE, p. 557-564. ISBN 1-86058-354-7.

[3] Nowack, M.L., "DESIGN GUIDELINE SUPPORT FOR MANUFACTURABILITY", "Engineering Department", Cambridge University, Cambridge, 1997, p.212.

[4] Charlton, C.T., "The Retrieval of Mechanical Design Information", "Engineering Department", Cambridge, Cambridge, 1999, p.165.

[5] Ahmed, S., Wallace, K.M. and Langdon, P.M. (2001) 'Identifying the strategic knowledge of experienced designers' in Strategic Knowledge and Concept Formation III, University of Sydney, Sydney, Australia, 31-53.

[6] Everitt, B. 1974, Cluster analysis. London: Heinemann Educational Books Ltd.

[7] Kruskal, J.B., and Wish, M, 1978, Multidimensional Scaling. Murray Hill, Bell Laboratories.

[8] Nosofsky, R. (1985). “Overall similarity and the identification of separable-dimension stimuli: A choice model analysis.” Perception & Psychophysics 35(5): 415-432.

[9] Kelly, G., 1963, The Psychology of Personal Constructs**,** New York: Norton.

[10] Gaines (1995). Knowledge Acquisition Tools based on Personal Construct Psychology, University of Calgary. 2002.

[11] Kaski, S., Honkela, T., Lagus, K., and Kohonen, T. (1998a). WEBSOM--self-organizing maps of document collections. Neurocomputing, volume 21, pages 101-117.

[12] T. Kohonen. Self-Organization Maps. Springer-Verlag, Berlin Heidelberg, 1995.

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