JS Gero and U Lindemann (eds), *Human Behaviour in Design'05*, 2005 Key Centre of Design Computing and Cognition, University of Sydney, pp 47-58

DESIGN BEHAVIOUR MEASUREMENT BY QUANTIFYING LINKOGRAPHY IN PROTOCOL STUDIES OF DESIGNING

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Abstract. This paper proposes approaches to measure linkography in protocol studies of designing. It outlines the ideas behind using clustering and Shannon's entropy as measures of designing behaviour. Hypothetical cases are used to illustrate the methods. The paper concludes that these methods may form the basis of a new tool to assess designer behaviour in terms of chunking of design ideas and the opportunities for idea development.

1. Motivation

The motivation of this exploration was to find a quantitative method to compare the team designing behaviour. Increasingly designers work across geographically distant locations, groupware and collaborative software have been developed to support temporally and geographically dispersed work teams. However, despite these developments, face-to-face interaction remains one of the most important elements in developing ideas (Salter and Gann 2002). Bly and Minneman (1990) together with other studies (Gabriel 2000; Vera et al. 1998) suggested that with the introduction of technology, designers will adapt their activities accordingly. These studies on team designing were mostly done at a macroscopic level and were not able to differentiate microscopic design behaviour. In order to develop tools that support the process of distant collaboration, a closer look at how design teams design is required as we currently have insufficient knowledge about these activities.

2. Linkography and its Use

Linkography is a technique used in protocol analysis to study designer's cognitive activities. It was first introduced to protocol analysis by Goldschmidt (1990) to assess design productivity of an individual designer. In this technique the design process is decomposed by parsing the recorded design protocol into small units of design moves. Goldschmidt defines a design move as: "a step, an act, an operation, which transforms the design situation relative to the state in which it was prior to that move" (Goldschmidt 1995), or "an act of reasoning that presents a coherent proposition pertaining to an entity that is being designed" . A Linkograph is then constructed by discerning the relationships among the moves to form links. It can be seen as a graphical representation of a design session that traces the associations of every design move. Figure 1 is an example of linkograph from Goldschmidt (1992). The design process can then be looked at in terms of the patterns of the linkograph which displays the structural design reasoning. Three distinct patterns had been identified: chunk, a group of moves that are almost exclusively links among themselves; web, a large number of links among a relatively small amount of moves; and sawtooth track, a special sequence of linked moves. Goldschmidt also identified two types of links: backlinks and forelinks. Backlinks are links of moves that connect to previous moves and forelinks are links of moves that connect to subsequent moves. Conceptually they are very different: "backlinks record the path that led to a move's generation, while forelinks bear evidence to its contribution to the production of further moves" (Goldschmidt 1995).

Link index and critical moves were devised as indicators of design productivity. Link index is the ratio between the number of links and the number of moves, and critical moves are design moves that are rich in links, they can be forelinks, backlinks, or both. In her exposition, design productivity is positively related to the link index and critical moves, that is, a higher value of link index and critical moves indicates a more productive design process. The rational was productive designers think through a group of interrelated issues before move on to another group of potentially interconnected issues, hence higher interconnectivity among move and higher number of critical moves. With this as a benchmark, Goldschmidt (1995) extended the use of linkography to compare individual design processes with team design processes.

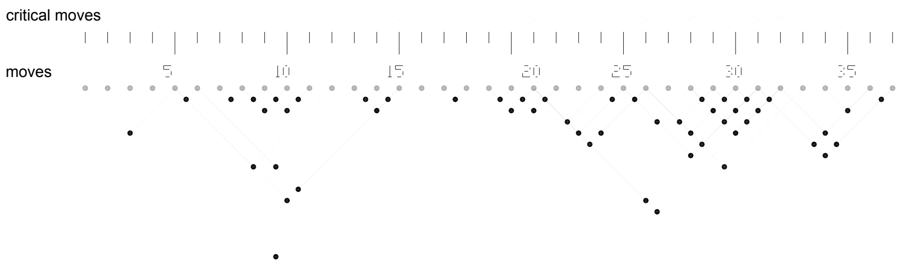


Figure 1. Linkograph from Goldschmidt (1992) with the position of critical moves indicated by "v".

2.1 DESIGN MOVES, IDEA GENERATION BEHAVIOUR, AND THE PROGRESS OF DESIGNI*N*G

What is an idea? How to define the boundary of an idea? Idea generation and creativity shared some common characteristics. Finke et al (1992) considered creativity not as a single unitary process but a product of many types of mental processes collectively setting the stage for creative insight and discovery. We consider design moves as the externalization of the mental processes. The collective moves can be seen as the clustering of interaction among ideas which can be seen as a behaviour characteristic of a design session. The progress of a design session can be observed through the analysis of the linkography. Linkography has been used for investigating the structure of design idea generation processes and for comparing design productivity (Goldschmidt 1990; Goldschmidt 1992; Goldschmidt 1995). Goldschmidt uses linkographs as a bridge between the design process and the design product so as to assess productivity.

Van der Lugt (2003) extended Goldschmidt's linkography to trace the design idea generation process and empirically verified the correlation between creative qualities of ideas and the well-integratedness of those ideas. He extended the linkography with link types: supplementary, modification, or tangential links corresponding to small alterations, same direction, or different directions association respectively. He found that a well-integrated creative process has a large network of links, a low level of self-links, and a balance of link types. Dorst (2004) traced linking behaviour of designers with regard to design problems and design solutions to reveal the reflective practice of designers.

With an understanding of the construction of a linkograph, one is able to comment on the design behaviour without studying the design protocol. Goldschmidt (1992) suggested that the linkograph pattern of productive designers will be different from that of less productive designers. Productive designers will elicit moves that have a high potential for connectivity to other moves, while less productive designers will have more random trails with moves that did not had a high potential for contribution to the design concept. Besides, designers start the design process with exploring different options and then select one to develop which will produce a very different linkograph compared to designers using a holistic approach without exploring different options. However, the interpretations of the linkograph lack objectivity.

3. Statistical Description of Linkography

If we take away all the linking lines in the linkograph in Figure 1 and only consider the linked nodes but not the moves, we will get nodes in a two dimension space, Figure 2. Treating each node as a point in the X-Y plane we can statistically describe a linkograph in terms of the total number of nodes, the mean values of X and Y – that is the centroid, and the deviations in X and Y axes.

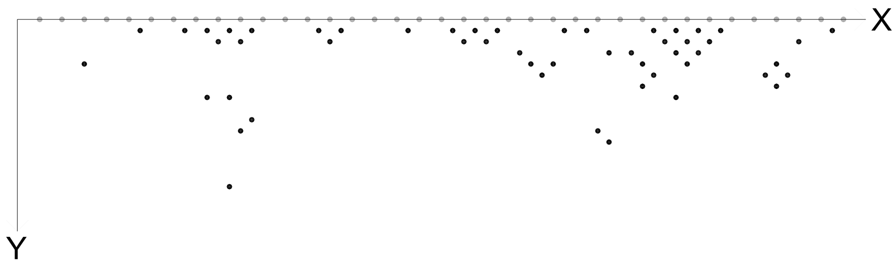


Figure 2. Reducing the graphical links to nodes in a 2 D space

The total number of linked nodes indicates the level of saturation of a linkograph. Normalizing this number against the number of moves will be the link index as described by Goldschmidt (1995). Table 1 and Figure 3 show the statistic scatter plot of the reduced linkograph.

TABLE 1. Descriptive statistic of the example linkograph

	N	Minimum	Maximum	Mean	Std. Deviation
X	52	3.00	36.50	22.01	9.41
Y	52	7.50	0.50	1.76	1.56

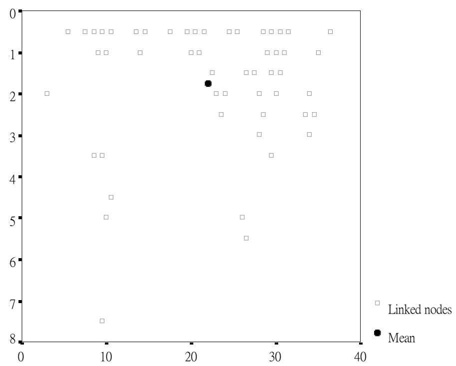


Figure 3. Scatter plot of the example linkograph with the mean value.

A higher mean value of X implies that more linked nodes appear at the end of a session and a lower value suggests that more linked nodes are present in the beginning of the session. A higher mean value of Y indicates longer linking lengths. However, the mean values do not include the dispersion of the distribution, therefore, we need to measure the standard deviations which suggest how concentrated the nodes are clustering around the means. The lower the value the closer those nodes are toward the mean. Tables 2 and 3 relate the appearance of linkographs, with the same number of nodes, to the statistical values.

TABLE 2. The shape of linkograph, with the same number of nodes, in relation to mean and standard deviation of X. A higher value of X-mean signifies there are more activities at the end of the session. [needs graphics inserted]

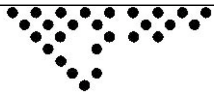
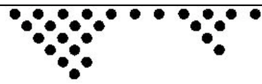
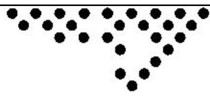
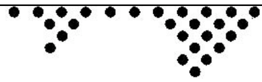
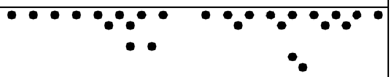
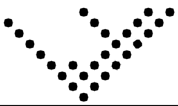
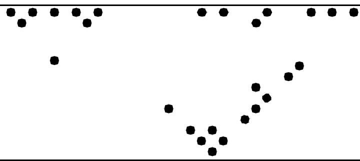
X (Moves) Axis	Small standard deviation (σ)	Large standard deviation (σ)
Small mean		
Large mean		

TABLE 3. The shape of linkograph, with the same number of nodes, in relation to mean and standard deviation of Y. A lower value of Y-mean indicates shorter linking distance.

Y (Links) Axis	Small standard deviation (σ)	Large standard deviation (σ)
Small mean		
Large mean		

3.1 CLUSTER ANALYSIS OF LINKOGRAPHY

As we can see in Tables 2 and 3 the linked nodes in a linkography may form clusters. These clusters resemble the chunks of ideas that are interlinked. We examine this with the example linkograph from Goldschmidt. There are two obvious chunks in this linkograph, the first chunk is from move 1 to move 18 and the second chunk from move 19 to 37.

TwoStep Cluster

SPSS TwoStep Cluster algorithm (SPSS 2002) is used in this study, this algorithm can handle both continuous and categorical variables. In the first step of this procedure, the records are pre-clustered into many small sub-clusters according to the selected criteria. Then, the algorithm clusters the sub-clusters created in the pre-cluster step into the desired number of clusters. If the desired number of clusters is unknown, it automatically finds the appropriate number of clusters according to the criteria. In this study the X (Moves) and Y (Links) variables were treated as continuous and Euclidean distance was used. Akaike's information criterion was used for clustering, and we did not assign the desired number of clusters. Figure 4 is the result, the TwoStep Cluster algorithm is able to discern the two chunks. Table 4 shows the cluster distribution and Table 5 shows the cluster profile.

TABLE 4. Cluster distribution of the example linkograph

		N	% of Combined	% of Total
Cluster	1	17	32.7%	32.7%
	2	35	67.3%	67.3%
	Combined	52	100.0%	100.0%
Total		52		100.0%

TABLE 5. Cluster profile of the example linkograph

Centroids		X		Y	
		Mean	Std. Deviation	Mean	Std. Deviation
Cluster	1	10.06	3.42	1.94	2.11
	2	27.81	4.59	1.67	1.24
	Combined	22.01	9.41	1.76	1.56

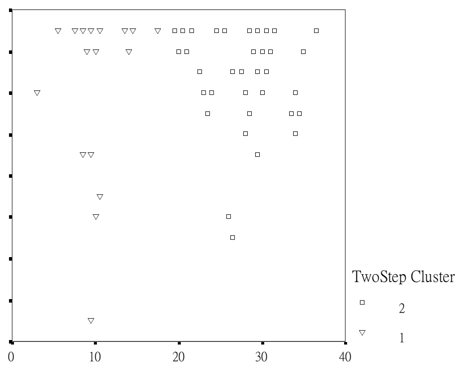


Figure 4. Scatter plot of the two clusters generated by the SPSS TwoStep Cluster algorithm.

4. Using Entropy to Measure Linkography

4.1 ENTROPY

In Shannon's (1948) information theory, the amount of information carried by a message or symbol is based on the probability of its outcome. If there is only one possible outcome, then there is no additional information because the outcome is known. Information can then be defined related to the surprise it produces or the decrease in uncertainty. Given that event E1 has a lower probability than event E2, I should be more surprised if E1 had occurred, hence I get more information. The entropy H, the average information per symbol in a set of symbols with *a priori* probabilities, is

$$H = p1*h(p1) + p2*h(p2) + \ldots + pN*h(pN) \quad (1)$$

Where $p_1, \ldots p_N$ are probabilities corresponding to $S_1, \ldots S_N$ states and h(p) is the information-generating function devised by Shannon which equals $-\log_b(p)$

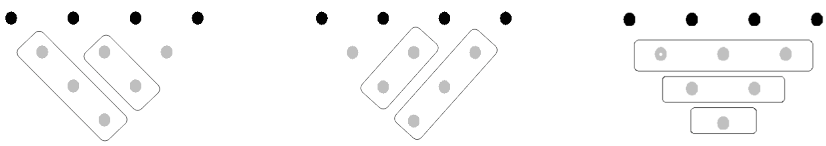
$$\text{Therefore } H = -\sum_{i=1}^{n} p_i \log_b(p_i) \quad \text{with} \quad \sum_{i=1}^{n} p_i = 1 \quad (2)$$

In this study we shall count entropy in rows of forelinks, backlinks, and horizontal links (horizonlinks) according to the ON/OFF of a link, Figure 5. Following Shannon's theory, formula (1), in each rows H becomes:

$$-p(ON)Log(p(ON)) - p(OFF)Log(p(OFF)) \quad \text{where } p(ON) + p(OFF) = 1 \; (3)$$

The reason for measuring forelink and backlink entropy is because of their conceptual differences as described in the previous section. Here we introduce another link type called *horizonlink*. Horizonlink bears the notion of length of the links which is a measure of time (separation) between linked moves or we can view it as a measure of the distances of the linked moves. This reflects the cohesiveness of the session.

The maximum entropy (most random) of each row occurs when the ON/OFF of the links are most unpredictable, that is, half of the nodes in the row are linked and half of the nodes in the row are un-linked. Figure 6 plots the value of H against formula (3).



(a) (b) (c)

Figure 5. (a) Measuring entropy of forelinks of each row, (b) measuring entropy of backlinks of each row, and (c) measuring entropy of horizonlinks.

The graph in Figure 6 is symmetrical, the slope of the graph decreases sharply as the probability moves away from 0 and 1. This indicates that when the links moves away from determinate values of 0 and 1 (all un-linked and all linked) the H value increases rapidly. In principle this is different from Goldschmidt (1995) interpretation of productivity where more critical moves (moves with more than 7 links) and high value of link index, disregard of the total number of possible link, are valued as more productive. However, Kan and Gero (2005) argue that a fully saturated linkograph indicates no diversification of ideas, hence less opportunity for quality outcomes. This graph shows that when *p*(1) is between {0.35, 0.65}, H is over 0.93 that is if the links in a row is in between 35% and 65% it will received a very positive value (rich design process). If the links is less then 5% or over 95%, it will receive a very low H value (below 0.29).

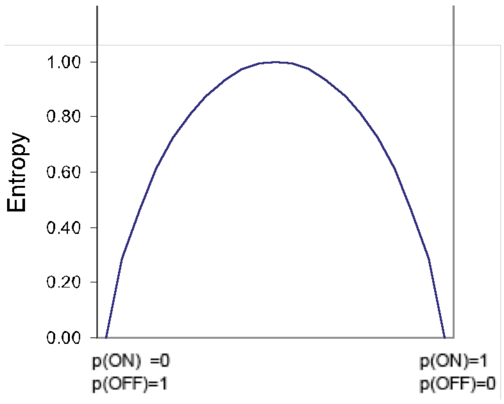


Figure 6. Maximum entropy when p(ON)=p(OFF)=0.5

In practice it is unlikely to have a fully saturated linkograph that has more than 7 moves. Figure 7 illustrates a typical linkograph in relation to the saturation of links; there are more *n* to *n-1* links than *n* to *n - i* links. The reason for that is people will try to maintain a coherent of conversation/thought in a conversation (Grice 1975; Pavitt and Johnson 1999) and people have limited short-term memory (Miller 1956).

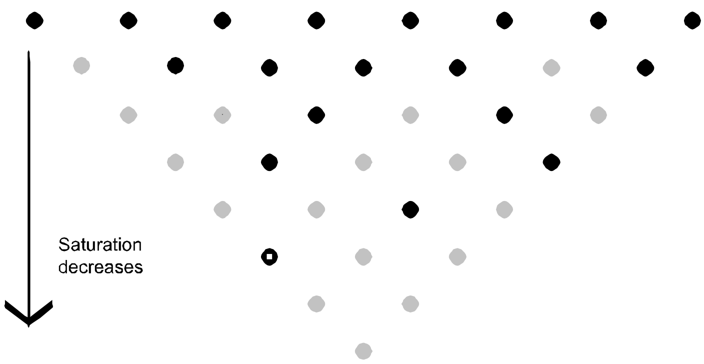


Figure 7. Typical distribution of links in a linkography of a design process

If we follow Miller's "magic number seven plus or minus two", any rows in a linkograph will seldom have more than 9 links. Taking the 35% linkage as denominator, therefore, any rows with row length more than 26 moves will not have a high H value.

This graph resembles the Wundt curve by Berlyne (1971), Figure 8. He used variables such as complexity or what he considered as surprise as stimuli that triggers curiosity. Berlyne's theory suggested that if the information received is too novel or too complex the hedonic value will decrease, hence less interesting.

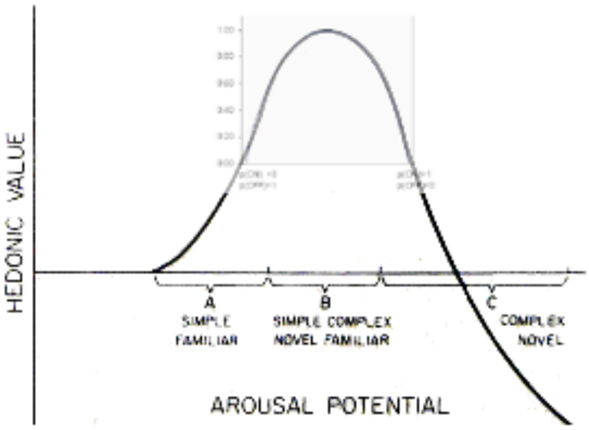


Figure 8. Wundt curve overlay with entropy curve.

Our hypothesis is that higher value entropy implies a process with more opportunities for ideas development.

4.2 HYPOTHETICAL CASES

Four hypothetical design scenarios with only five moves or four stages are used to examine these concepts further. Table 6 shows some of the possible linkographs together with the interpretation of the design processes they encapsulate. Tables 7, 8, and 9 are the entropy, using formula (3), of the forelinks, backlinks, and horizonlinks respectively. Table 10 is the cumulative entropy which maps well on to our understanding of those scenarios.

5. Conclusion

Studies in design collaboration (Cross and Cross 1995; Gabriel 2000; Olson and Olson 2000; Oslon et al. 1992; Zolin et al. 2004) had shown that there is a multiplicity of factors that contribute or affect the process and product of the collaboration. Some of the factors are: role and relationship, trust, social

TABLE 6. Some possible linkographs of five design moves and their interpretations.

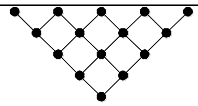
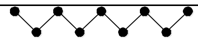
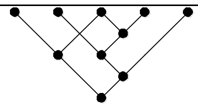
Case 1		Five moves are totally unrelated; indicating that no converging ideas, hence very low opportunity for idea development.
Case 2		All moves are interconnected; this shows that this is a total integrated process with no diversification, hinting that a pre-mature crystallization or fixation of one idea may have occurred, therefore also very low opportunity for novel idea.
Case 3		Moves are related only to the last one. This indicates the process is progressing but not developing indicating some opportunities for ideal development.
Case 4		Moves are inter-related but also not totally connected indicating that there are lots of opportunities for good ideas with development.

TABLE 7. Entropy of forelinks

	Forelink Entropy				
	Move 1	Move 2	Move 3	Move 4	**Total**
Case 1	0	0	0	0	**0**
Case 2	0	0	0	0	**0**
Case 3	0.811	0.918	1.000	0	**2.730**
Case 4	1.000	0.918	1.000	0	**2.918**

TABLE 8. Entropy of backlinks

	Backlink Entropy				
	Move 2	Move 3	Move 4	Move 5	**Total**
Case 1	0	0	0	0	**0**
Case 2	0	0	0	0	**0**
Case 3	0	1.000	0.918	0.811	**2.730**
Case 4	0	1.000	0.918	1	**2.918**

TABLE 9. Entropy horizonlinks

	Horizonlink Entropy			
	n-1	n-2	n-3	**Total**
Case 1	0	0	0	**0**
Case 2	0	0	0	**0**
Case 3	0	0	0	**0**
Case 4	0.811	0.918	1.000	**2.730**

TABLE 10. Cumulative entropy of each case

Case 1	Case 2	Case 3	Case 4
0	0	5.459	8.566

skills, common ground, organization context, and socio-technical conditions. Most of these factors are underpinned by communication, either verbal or non-verbal, with or without technological mediation.

We selected linkography as a tool to re-represent the communication content and then abstract information out of the linkograph. The advantage of using linkography is twofold. First it is scalable in two dimensions, 1) this method is not tied to the number of designers being studies. Goldschmidt (1995) used linkography to compare the process of three designers with the process of a single designer, and 2) the length of the linkograph can be of any duration. Second it is flexible, the design moves and how the design moves are linked can be coded separately depending on the focus of the study (Dorst 2004; Kan and Gero 2004; Van-der-Lugt 2003). These studies are either done qualitatively or at the macroscopic level.

In this paper we outlined two approaches to measure linkograph which reflect the idea development behaviour of a design session. Cluster analysis was able to discern the number of chunks in a linkograph. In the entropy measurement, we proposed to measure three types of links. Forelink entropy measures the idea generation opportunities in terms of new creations or initiations. Backlink entropy measures the opportunities according to enhancements or responses. Horizonlink entropy measures the opportunities relating to cohesiveness and incubation. These approaches form the basis of a new tool to assess designer behaviour and provide the opportunity to study the impact of various forms of computational technology on collaborative design. This will provide feedback to both the developers and users of these tools.

Acknowledgement

This research is supported by an International Postgraduate Research Scholarship, University of Sydney, and the CRC for Construction Innovation project titled: Team Collaboration in High Bandwidth Virtual Environments.

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