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ENTROPY MEASUREMENT OF LINKOGRAPHY IN PROTOCOL STUDIES OF DESIGNING

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Abstract. This paper explores the use of information theory to measure linkography in protocol studies of designing. It outlines the ideas behind using Shannon's entropy as a measure of opportunities for idea development in team designing. The entropy measurement can be used to assess a whole design session or it can be used to evaluate the progress of a session by taking incremental measurements. Two cases are used to illustrate this method. The paper concludes that this method is able to assign signatures to design sessions that characterize the opportunities for idea development.

1. Protocol Studies in Designing

According to Akin (1998) the first formal protocol analysis that study designing was conducted by Charles Eastman (1969). Eastman's study contributed to the current understanding of what architects do when they design in the form of a information process model. Eastman's view had been challenged by Schon and Wiggins (1992) which suggested designing as a reflective conversation with material, that the basic structure of information flow is interactive. Cross (2001) gave a summary of design cognition from the results of interdisciplinary protocol and other empirical studies of design activity in the past thirty year and asserted that protocol analysis has become the most likely method to study cognitive activities of designers. Dorst and Dijkhuis (1995) suggested there were two types of protocol studies namely process- and content- oriented protocol analysis to capture the two different paradigms mention above. Linkography was first introduced to protocol analysis by Goldschmidt (1990) to assess design productivity of designers where she suggested linkograph acts as a bridge between the design process and the design product for assessment (Goldschmidt 1992). In a way this method bridged the process and content oriented protocol analysis of designing. The following section gives a summary of linkography relevant to this paper, readers should refer to Goldschmidt (1990, 1992) for further details of this method.

2. Linkography

In this technique the design process is decomposed by parsing the recorded design protocol into small units called 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" (Goldschmidt 1992). 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.

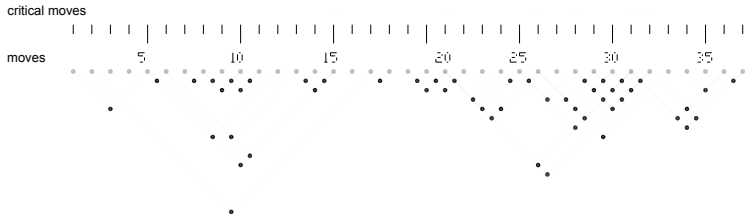


Figure 1. Linkograph from Goldschmidt (1992) with the position of critical moves indicated by "v".

Goldschmidt 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).

We consider design moves as the externalization of the mental processes. The collective moves can be seen as the clustering of interaction among ideas. The progress of a design session can be observed through the analysis of the linkography. 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 a productive designer will be different from that of a less productive designer. 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 (Goldschmidt 1992). Besides, designers start the design process by 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. The interpretations of the linkograph lacks objectivity. We propose to use Shannon's entropy as a measure of the linkograph and we start the exploration with two case studies of team designing.

3. Case Studies

Two pilot cases were conducted to investigate the use of entropy as a measure of the design session. Case data was obtained from the CRC for Construction Innovation project titled: Team Collaboration in High Bandwidth Virtual Environments. Both cases involved design teams collaborating over an architectural project with different conditions.

Case I was a in-situ design session carried out in a Sydney architectural office. Two architects, one more senior than other, were involved in the design of a commercial building in Canberra city centre. This design session occurred after a review and planning session subsequent to a client meeting. In this session the designers revisited the relationship between vertical circulation and the void areas so as to satisfy the client's preference. The raw data was the video recording. Figure 2 is one image from this session and Figure 3 is the first sheet of drawing that they produced in this session, which will be analysed in this paper.

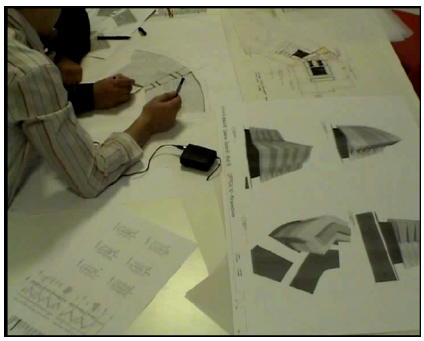


Figure 2. Face-to-face session, Senior Architect starts drawing the core and the bridges after 4 minutes.

3.1. QUALITATIVE ANALYSIS OF THE FACE-TO-FACE SESSION

During the first 10.5 minutes of the session, the designers frequently used drawing and gesturing to communicate without explicit verbalizing, and nearly all verbal protocols were accompanied by non-verbal actions; they referred to materials from previous designs; they drew different types of diagrams, sometimes separately; and they referred back and forth to the main plan drawing. Design actions were occurring in parallel, sometimes when the

Senior Architect was working on the large drawing the Architect would draw on another sheet of paper or retrieved older drawings. There were interruptions like setting up of the microphone for recording at the beginning and a phone call for about a minute towards the end. The leadership role was clear, the Senior Architect controlled and led the session. The designers were dealing more with the structural or formal aspect in this session – where things should be and how they related to each other so as to satisfy the client.

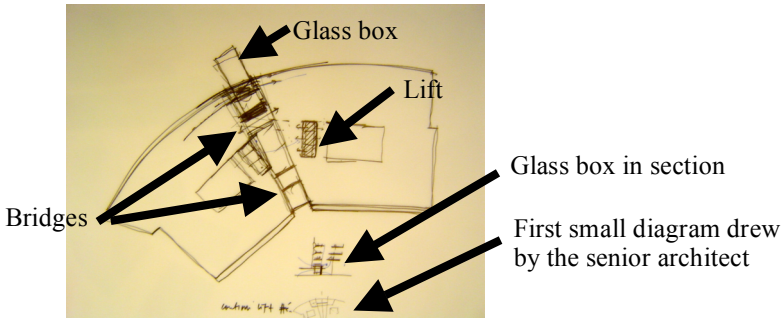


Figure 3. The first page of drawing the architects produced in the first 10.5 minutes with annotation added; this sheet was mostly drawn by the Senior Architect, the other Architect had a small diagram on another sheet.

Case II was a in-vitro session which simulated distant collaboration of two designers, an Architect and a Landscaper, with the use of computer-mediated tools. Tangible interfaces, Smartboard and Mimio, together with Microsoft NetMeeting were used in this experiment. NetMeeting contains a shared whiteboard and a video conferencing tool. The designers were asked to design an art gallery in a harbour front triangular site with level changes. Both their displays and actions were recorded as shown in Figure 4. Figure 5 is the first page that they produced which will be studied and compared in this paper; annotation is added to show the meaning of their drawing.

3.2. QUALITATIVE ANALYSIS OF THE NETMEETING SESSION

In this session the designers were given a new design task, so they were focusing more on the functional or conceptual aspect of the design with time spent on studying the brief. Figure 5 is the capture of the first page from the screen and the annotation was added by consulting the protocol. Overall we can observe that the Architect took the leadership role in this session and did most of the drawing. In the NetMeeting session interactions were more sequential and consisted of more affirmations compared to the face-to-face session and there was not much gesturing. There were more interactions among ideas, drawings, gestures, and verbal communications in the face-to-face session. A more detailed analysis of both sessions can be found in Kan and Gero (2005a).

Figure 4. Case II, NetMeeting session, the designers translating the issues into drawing in the beginning of the session

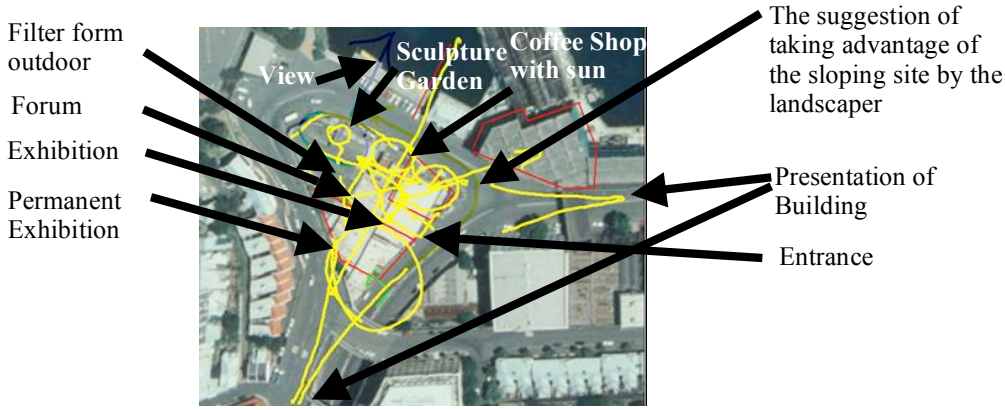


Figure 5. The first page of the NetMeeting session, mostly drawn by the Architect

3.1. LINKOGRAPHY OF THE TWO SESSIONS

There are 98 moves in the first 10.5 minutes with 299 links to produce the first page of drawing in the face-to-face session. In the NetMeeting sessions they took 6.5 minutes to produce the first page with 97 moves and 277 links. Figures 6 and 7 show the linkographs of the two sessions.

We can observe from the linkographs that in the face-to-face session links are more intense over the whole session where as in the NetMeeting session links are dense towards the end of the session. There is an obvious chunk, at the beginning of the NetMeeting session, but not in the face-to-face session. Overall the linkograph of the face-to-face session is more integrated but in the NetMeeting session there are sequential groups of moves.

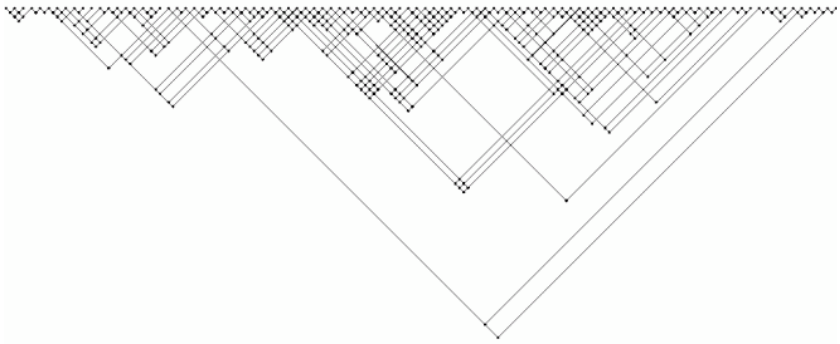


Figure 6. The linkograph of the first 10.5 minutes of the face-to-face session

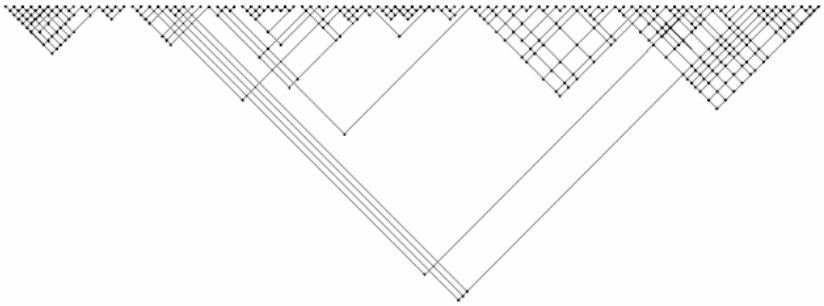


Figure 7. The linkograph of the first 6.5 minutes of NetMeeting session

4. Entropy Measurement and Interpretations

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 measure entropy in rows of forelinks, backlinks, and horizontal links (horizonlinks) according to the ON/OFF of a link, Figure 8. Following Shannon's theory, formula (1), in each rows H becomes:

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

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 9 plots the value of H against formula (3).

Figure 8. (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 9 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's (1995) interpretation of productivity where more critical moves (moves with more than 7 links) and high value of link index, irrespective of the total number of possible link, are valued as more productive. Kan and Gero (2005b) 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 are in between 35% and 65% it will received a very positive value (rich design process). If the links are less then 5% or over 95%, it will receive a very low H value (below 0.29).

In practice it is unlikely a fully saturated linkograph will have more than 7 moves. Figure 10 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.

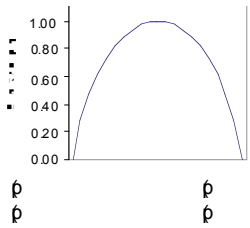


Figure 9. Maximum entropy when p(ON)=p(OFF)=0.5

Figure 10. Typical distribution of links in a linkography of a design process

The reason for that is people will try to maintain a coherence of conversation/thought in a conversation (Grice 1975; Pavitt and Johnson 1999) and people have limited short-term memory (Miller 1956).

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 11. He used variables such as complexity or what he considered as surprise as stimuli that triggers curiosity.

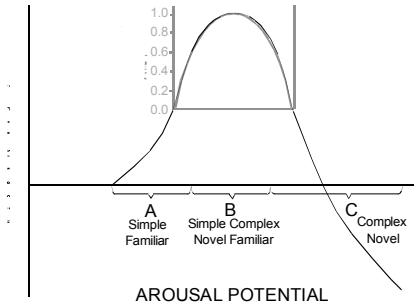


Figure 11. Wundt curve overlay with entropy curve.

Berlyne's theory suggested that if the information received is too novel or too complex the hedonic value will decrease, hence less interesting. Our hypothesis is that ahigher entropy implies a process with more opportunities for ideas development.

4.1. HYPOTHETICAL CASES

Four hypothetical design scenarios with only five moves or four stages are used to examine these concepts further. Table 1 shows some of the possible linkographs together with the interpretation of the design processes they encapsulate. Tables 2, 3, and 4 are the entropy, using formula (3), of the forelinks, backlinks, and horizonlinks respectively. Table 5 is the cumulative entropy which maps well on to our understanding of those scenarios.

TABLE 1. Some possible linkographs of five design moves and their interpretations.

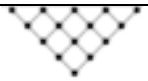
Case 1		Five moves are totally unrelated; indicating that no converging ideas, hence very low opportunity for idea development.
Case 2		All moves are interconnected, this shows that this is a total integrated process with no diversification, hinting that a pre-mature crystallization or fixation of one 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 2. 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 3. 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 4. 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 5. Cumulative entropy of each case

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

5. Entropy of Face-to-face and NetMeeting Sessions

Table 6 shows the entropy of the Face-to-face and NetMeeting sessions. Forelinks can be seen as initiations and backlinks as responses. So a higher H value of forelinks signifies higher opportunity in initiating design moves, and a higher H value of backlinks denotes higher opportunity in building upon previous design moves. The horizonlink entropy indicates the opportunity according to the length of the links, high values usually indicate a mixture of long and short links which suggests the cohesiveness and incubativeness of ideas. In the Face-to-face session the backlink entropy is higher than the forelink entropy which indicates higher opportunity of building upon than initiating moves. The NetMeeting session scored the opposite, the initiation opportunity is higher than the response opportunity. These match our qualitative analyses of both sessions. In the Face-to-face session they were in the stage of refining the design, referring to what is already there, whereas in the NetMeeting session they started from the beginning, initiating new ideas there. Both sessions have similar horizonlink entropy. Overall, the face-to-face session has a higher entropy in all three areas implying the opportunities are higher in all the areas.

TABLE 6. Entropy of the two sessions.

	Forelinks total H	Backlinks total H	Horizonlinks total H	Cumulative Total H
Face-to-face	34.17	36.69	12.24	**83.10**
NetMeeting	28.00	27.23	11.62	**66.85**

5.1. INDIVIDUAL ENTROPY CONTRIBUTION AND ROLE

Tables 7 and 8 show the forelinks and backlinks entropy contributions by different participants. In both sessions the leaders scored higher than their partners in both forelinks and backlinks entropy. There are two factors that

contribute to this: the number of moves and the entropy per move. From our qualitative analysis we know the leaders did most of the drawing, hence contribute more moves. The leaders also have a higher entropy per move except for the forelinks of the Landscaper. This is due to the Landscaper's contribution of an new idea – taking advantage of level changes which is an opportunistic initiation. The individual's entropy score faithfully reflected their opportunistic contributions.

TABLE 7 Forelink and backlink entropy by individuals in the Face-to-face session

	Moves	Forelink H per move		Backlink H per move	
Senior Architect	60	21.661	0.361	22.846	0.381
Architect	38	12.511	0.329	13.847	0.364

TABLE 8 Forelink and backlink entropy by individuals in the NetMeeting session

	Moves	Forelink H per move		Backlink H per move	
Architect	60	16.582	0.276	17.930	0.299
Landscaper	37	11.283	0.305	8.988	0.243

6. Changes of Entropy During Session

As we observe the linkographs of Figures 6 and 7, it is easy to infer that the entropy varies across the time line. There are two approaches to measure this change, one using a fixed time frame as a reference window and the other use a fixed number of moves as the width of window. We use the latter because it is easier to operate and give more meaningful comparison. If we calculate the entropies within a 7 moves window as in Figure 12, we can record the changes of entropy across the design session. In this method we neglect those linked nodes outside the window, which is outside the shaded triangle. The 7 moves cut is indicative rather than conclusive. In the following sections we shall empirically derive a suitable moves window width to get meaningful results. By monitoring the change of entropy we can study the trend of a design session.

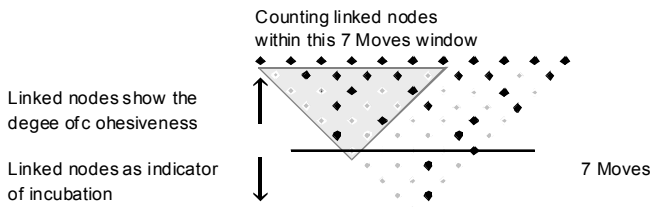


Figure 12. Using a 7 moves window to calculate the entropies.

6.1. DESIGN MOVES AND SHORT-TERM MEMORY

Miller (1956) demonstrated that the chunk of information hold in short-term memory was limited to seven plus or minus two. There are other more articulated models of memory model like Paivio (1986), Baddeley (1986), and Logie (1995, 2001) that use the term working memory rather than short-term memory so as to describe it better. Baddeley's model of working memory contains three parts, the visuo-spatial sketch pad, the phonological loop, and the central executive. Logie's developed Baddeley's model to consider knowledge, long-term memory representation, as a filter that will bias perceptions before getting into the three parts of working memory. It remains that the content of this memory degrades rapidly, in general it is believed it holds information for about 12 to 20 seconds. Important or interesting information will be sustained in the working memory and trigger further associations in the memory system. As we assume that moves are selected externalization of the designers' cognitive processes so as to communicate with their partners, the cognitive processes that correspond to the moves can be in the working memory or in the long-term memory. When these processes are in working memory the corresponding moves will have high interconnectivity.

6.2. DETERMINING THE WIDTH OF MOVES WINDOW

Following Miller's magic number seven, we started experimenting with the change of entropy with a window width of 7. However, this moves-entropy variation is such that it is hard to detect any obvious trend. So we increased the window width to smooth the graph, when the moves window was widen to 28 moves, with the value of the entropy is normalized by dividing it by 28 to produce the average entropy per move, Figures 13 and 14 were obtained. There is a steady increase of all the links entropies in the NetMeeting session at the beginning followed by a shaper raise at the end. In general the Face-to-face session the entropies increase and peak approximately in the middle of the session and then decrease. The horizonlink entropy has two obvious peaks.

8. Conclusion

Studies in design collaboration (Cross and Cross 1995; Gabriel 2000; Olson and Olson 2000; Oslon et al. 1992; Zolin et al. 2004) have 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 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. The communication content can serve as a window to observe the individual's cognitive

processes (Cross et al. 1996). We selected linkography as a tool to re-represent the communication content and then use entropy to measure the linkograph. The advantages of using linkography are twofold. First, it is scalable in two dimensions, 1) the method is not tied to the number of designers being studies. Goldschmidt (1995) used linkography to compare the processes 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 in that 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).

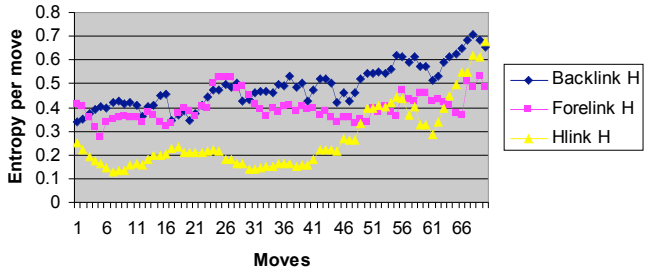


Figure 13. Change of entropy in NetMeeting session with 28 moves as window.

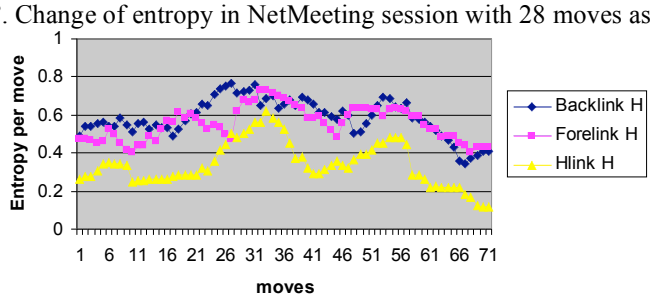


Figure 14. Change of entropy in Face-to-face session with 28 moves as window.

7. Further Investigation of the Change of Backlink Entropy

We further examine these trends by fitting them into a polynomial function. The backlink entropies with 28 moves window were assigned as an array in MatLab. Using MatLab's supervised polynomial fit function, a 4th degree polynomial was obtained, Figures 15 and 16.

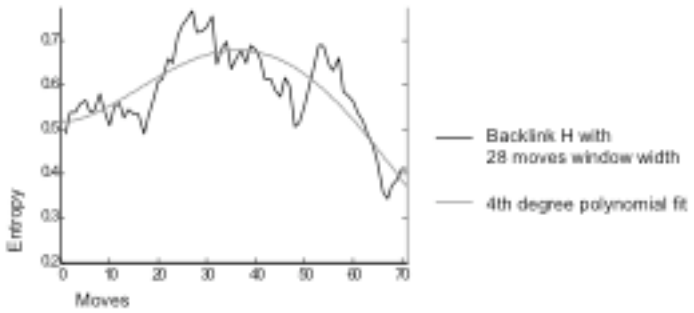


Figure 15. Changes of backlink entropy during the face-to-face session. 28 moves was used as a window for entropy measurement.

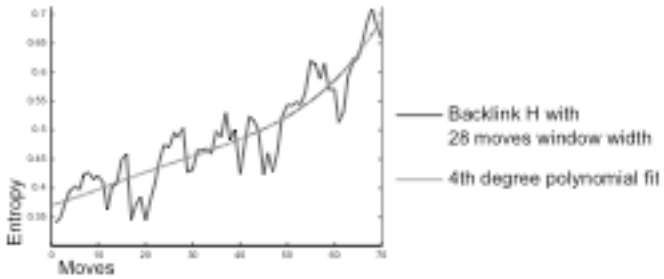


Figure 16. Changes of backlink entropy during the NetMeeting session. 28 moves was used as a window for entropy measurement.

Since the scale of the entropy axis of Figures 15 and 16 is different, we re-plotted the two polynomial curves with the same scale in Figure 17 for comparison. The form of the two polynomials is very different. The rate of change of entropy of the NetMeeting session is always positive while the second half of the face-to-face session is negative, Figure 18. The Face-to-face session has a higher backlink entropy while the NetMeeting session has a higher positive rate of change of entropy. This is confirmed by using adaptive Simpson quadrature in MatLab to calculate the areas of under the curves in Figure 18. The areas are 0.032 for the face-to-face session and 0.162 for the NetMeeting session

In this paper we proposed the use of Shannon's entropy to measure linkographs as an indicator of the idea development opportunity in a design session. We outlined the idea behind this approach and suggested measuring three types of links. Forelink entropy measures the idea generation opportunities in terms of new creations or initiations.

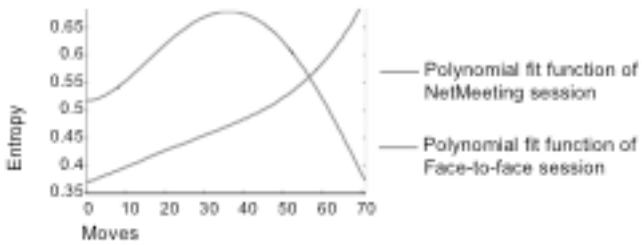


Figure 17. Plotting the backlink entropy polynomial fit of the two sessions with the same scale.

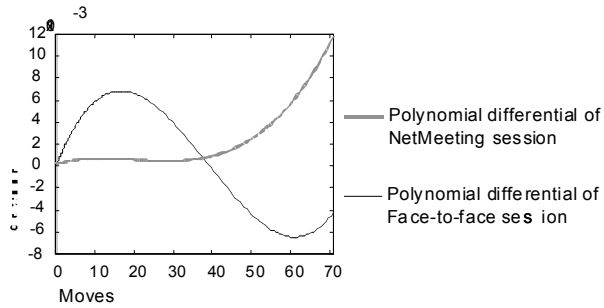


Figure 18. The polynomial differential, representing the rate of change, of the backlink entropy in both sessions.

Backlink entropy measures the opportunities according to enhancements or responses. Horizonlink entropy measures the opportunities relating to cohesiveness and incubation. We also measured the variations of entropy of these links within a session; it can be observed that the two sessions produced very different shapes of moves-entropy graphs. This can be seen as the signature of a design session. Further investigation is required for discerning the meaning of this signature. For example if the rate of change of the move-entropy graphs is negative, does it mean that it is a converging process since the idea development opportunity is getting less and less? Our approach may form the basis of a new tool to assess designers and design sessions and may provide the opportunity to study the impact of various forms of computational technology on collaborative design.

Acknowledgement

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