Acquiring information from linkography in protocol studies of designing

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This paper proposes methods to acquire information from linkography in protocol studies. The paper commences with an introduction of linkography together with its use and then presents two cases of collaborative designing. A qualitative analysis of these cases and their linkographs is presented. Two different strategies to abstract information from the linkographs are described: one based on clustering and the other based on Shannon's entropy. The abstracted information is interpreted and mapped to the qualitative analysis of the protocols. The results are promising; cluster analysis is able to group the linkograph into meaningful clusters, while entropy measures the opportunities for idea development of a team and can also reflect the opportunistic contributions of individual participants.

Keywords: design studies, research methods, case study, linkography, collaborative design

The motivation for this research is to develop quantitative methods to compare cognitive aspects of team designing processes. Increasingly designers work across geographically distant locations. Groupware and collaborative software have been developed to support temporally and geographically dispersed work teams. 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 (Vera et al., 1998; Gabriel, 2000) suggested that with the introduction of technology, designers will adapt their activities accordingly. These studies of team designing were mostly done at a macroscopic level and were not able to differentiate microscopic design activities. In order to develop tools that support the process of distant collaboration, a closer look at how design teams engage in designing is required as we currently have insufficient knowledge about these activities.

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Studies such as Cross and Clayburn Cross (1995), Gabriel (2000), Olson and Olson (2000), Oslon et al. (1992), and Zolin et al. (2004) show that there is a multiplicity of factors that contribute to or affect team designing. Some of

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these are as follows: role and relationship, trust, social skills, common ground, organizational context, and socio-technical conditions. Most of these factors are underpinned by communication, either verbal or non-verbal, with or without technological mediation. We use linkography to re-represent the communication content and then abstract information from the linkograph by statistical analysis and a method derived from information theory.

1 Linkography and its use

Linkography is a technique used in protocol analysis to study a 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 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. The design process can then be looked at in terms of the patterns in the linkograph which display the structure of design reasoning. Three distinct patterns had been identified: *chunk*, a group of moves that are almost exclusively linked among themselves; *web*, a large number of links among a relatively small number 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 either 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. Goldschmidt (1995) extended the use of linkography to compare individual design processes with team design processes.

To give an example of linkography, Table 1 contains a transcript extracted from a computer-mediated collaboration (NetMeeting) design session. In this session an Architect (A) was collaborating with a Landscaper (L) to design an art gallery in a harbour-front triangular site with level changes. The design session was recorded and each utterance from the designers was transcribed and tagged sequentially as a design move, A01 is the first move by the Architect and L01 is the first move by the Landscaper in this extracted protocol; A02 is the second

Table 1 Extract from the transcript at the early stage of the session

A01	The north is up the page, so the best sun is down the page
L01	For the gallery space
A02	Yeah, yeah
A03	So can you see my mouse, my pointer
L02	Can I see your mouse?
A04	My pointer
L03	Yeah well I can see a pointer…is that mine?
A05	That's yours but you don't see me moving it
L04	No
A06	Ok that mean I've to draw

move, and so on. Utterances with more than one intention are divided into smaller units of design moves such as in A02 and A03. A02 was a confirmation of L02's response while in A03 the Architect was starting another theme. Links can be established among those moves by posing one question: is move N related to other moves from 1 to $N-1$? The links are represented by joining the moves with lines and dots; moves are represented by dots. For example L01, '*for the gallery spaces*', was a response to A01, '*the north is up the page, so the best sun is down the page*', therefore A01 and L01 are linked. However, when the Architect asked the Landscaper whether she saw his mouse in A03, this move was not related to any earlier moves so there was no link between A03 and the previous moves, by iterating the same process through all the moves, the linkograph in Figure 1 can be constructed.

There are two advantages in using linkography for studying design protocols. 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 in accordance with any prescribed duration. In our two case studies it was according to the first sheet of their drawing. 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. See Dorst (2004), Kan and Gero (2004), and Van-der-Lugt (2003); these studies were done either qualitatively or at the macroscopic level.

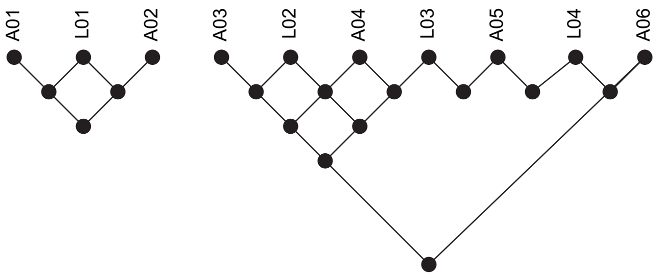


Figure 1 A linkograph for the corresponding transcript in Table 1

2 Design moves, idea generation, and the progress of designing

What is an idea? How to define the boundary of an idea? Idea generation and creativity share 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 interactions among ideas. The progress of a design session can be observed through the analysis of linkographs. Linkography has been used for investigating the structure of design idea generation processes and for comparing design productivity (Goldschmidt, 1990, 1992, 1995). Van-der-Lugt (2003) not only extended Goldschmidt's linkography to trace the design idea generation process but also empirically verified the correlation between creative qualities of ideas and the well-integratedness of those ideas. He extended linkography with link types: supplementary, modification, or tangential links corresponding to small alterations, same direction, or different direction associations, 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 process without studying the design protocol. Designers who start the design process by exploring different options and then select one to develop, will produce a very different linkograph compared to designers using a holistic approach without exploring different options. However, the interpretations of a linkograph lack objectivity. There are different levels of subjectivity: determining the moves (segmentation), judging the links among moves (coding), and interpreting the meaning of the resulting linkograph (analysis). Most design protocol studies rely on inter-coder arbitration (McNeill et al., 1998), to ensure protocols are objectively segmented and coded. Van-der-Lugt (2000) has attempted to strive for reliability in linking by introducing a series of indicators for links. The interpretation of a linkograph is usually narrated with the aid of link index and critical moves. In this paper we are concerned with the interpretations of linkographs and consider the possibility of using objective methods to acquire information from the linkograph. We start with two case studies.

3 Case studies

Two pilot case studies were conducted to investigate the kinds of information that can be abstracted from linkographs other than link index and critical moves. Case data was obtained from the CRC for Construction Innovation project titled: Team Collaboration in High Bandwidth Virtual Environments.

This section describes the two design sessions together with the qualitative analyses of the sessions. Both cases involved design teams collaborating on an architectural project under different conditions.

3.1 Case I: face-to-face design session

Case I was an *in situ* design session carried out in a Sydney architects' office. Two architects, one more senior than the other, were involved in the design of a commercial building in Canberra's 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 a video recording of the session. 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 analyzed in this paper.

3.1.1 Qualitative analysis of the face-to-face session

In this session the architects were refining the design after the client's feedback. During the first 10.5 min of the session, the designers frequently used drawing and gesturing to communicate without explicit verbalizing, and nearly all verbalisations 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 occurred in parallel. Sometimes when the Senior Architect was working on the large drawing the Architect would draw on another sheet of paper or retrieve older drawings. There were interruptions such as 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 session started with the Architect suggesting a few

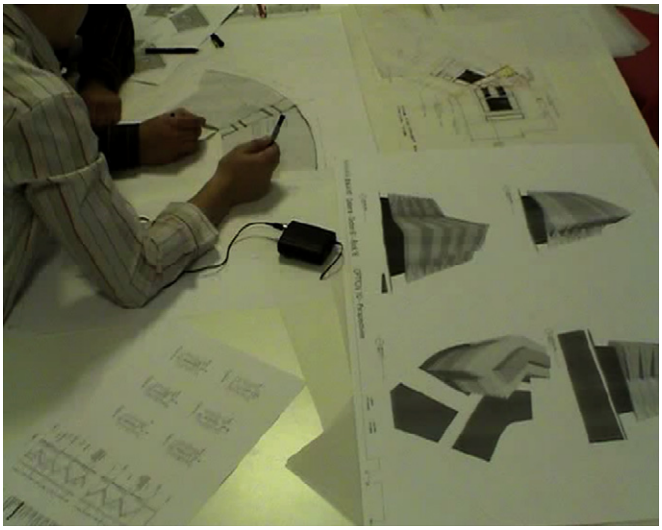


Figure 2 Face-to-face session, Senior Architect starts drawing the core and the bridges after 4 min

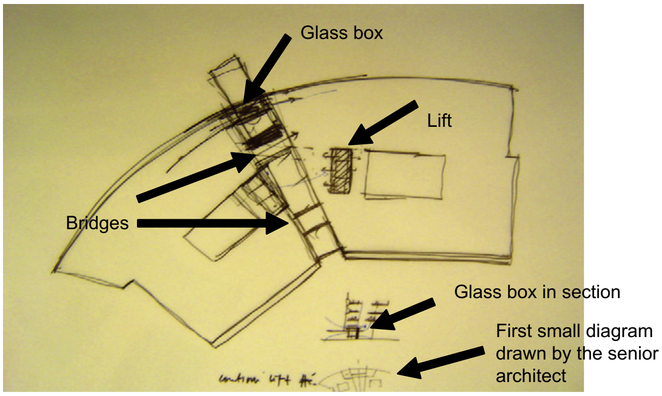


Figure 3 The first sheet of drawing the architects produced in the first 10.5 min with annotation added; this sheet was mostly drawn by the Senior Architect, the other Architect had a small diagram on another sheet

possible solutions or moves related to the previous session but the Senior Architect insisted on not jumping to a conclusion and started revisiting the issues and the client's preference by drawing a small plan at the bottom of the sheet. He then traced over the position of the bridges which he regarded as important. Then they discussed the relationship among the lift, void, bridges, and lobby. After about 6 min the Senior Architect discovered another problem with the setback of columns. They explored the position of the glass box and its relationship with other levels by drawing a small section with the setback of columns. The designers were dealing more with the structural or formal aspects of the design in this session – where things should be and how they related to each other so as to satisfy the client.

3.2 Case II: NetMeeting design session

Case II was an *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 sheet that they produced which will be studied and compared in this paper; annotation is added to show the meaning of the drawing.

3.2.1 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. The Architect started the session by trying to figure out the scale of the site in relationship to the brief. He complained that there was nothing there to scale with, and he could only do a mockup. The Landscaper proposed to work out only the appropriate relationship of functional space and its approximate sizes. The Architect then started reading the brief aloud with his added interpretation. Following that the Architect clarified with his

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

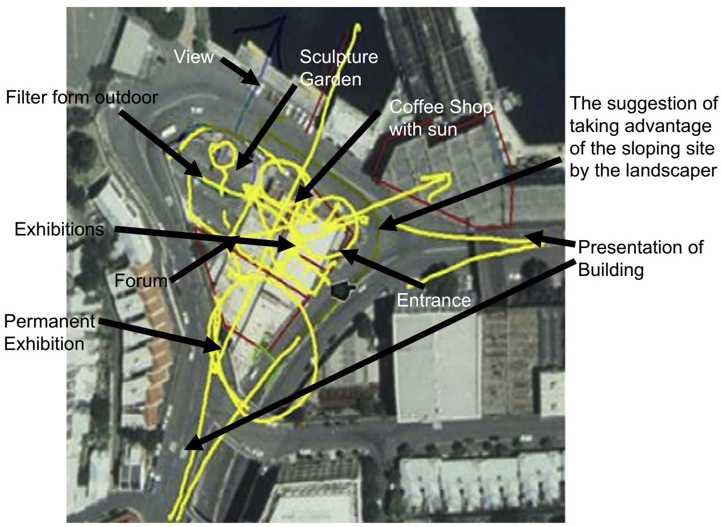


Figure 5 The first sheet of the NetMeeting session, mostly drawn by the Architect

partner if she could see his pointer and started drawing. He started drawing, proposing the main exhibition area on the south side of the site. The Landscaper noticed that there was a level change in the site and suggested taking advantage of that. Reacting to the suggestion the Architect proposed the location of the central courtyard, entrance, and connectivity. Then within the final 1.5 min the Architect produced all the rest of the design in the first sheet with the contribution of the Landscaper, that included the exhibition areas, the coffee shop with northern sun, the sculpture garden with a view, and the forum. 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.

3.3 Linkography of the two sessions

Ninety-eight moves were made in the first 10.5 min, with 299 links, to produce the first sheet of drawing in the face-to-face session. Of these 98 moves, the Architect contributed 38 moves and the Senior Architect contributed 60 moves. In the NetMeeting sessions they took 6.5 min to produce the first sheet, with 97 moves and 277 links. The Landscaper contributed 37 moves and the Architect contributed 60 moves. 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 denser over the whole session whereas in the NetMeeting session links are dense towards the end of the session. There is an obvious chunk at the beginning of the

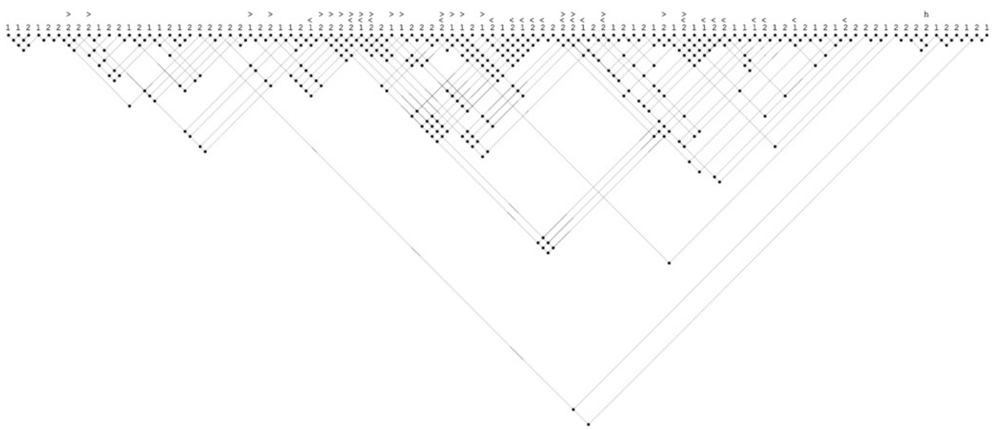


Figure 6 The linkograph of the first 10.5 min of the face-to-face session with ‘1’ represents the Architect and ‘2’represents the Senior Architect. The critical moves with more than five links (CM^5) are indicated by: ‘>’ for forelinks and ‘<’ for backlinks

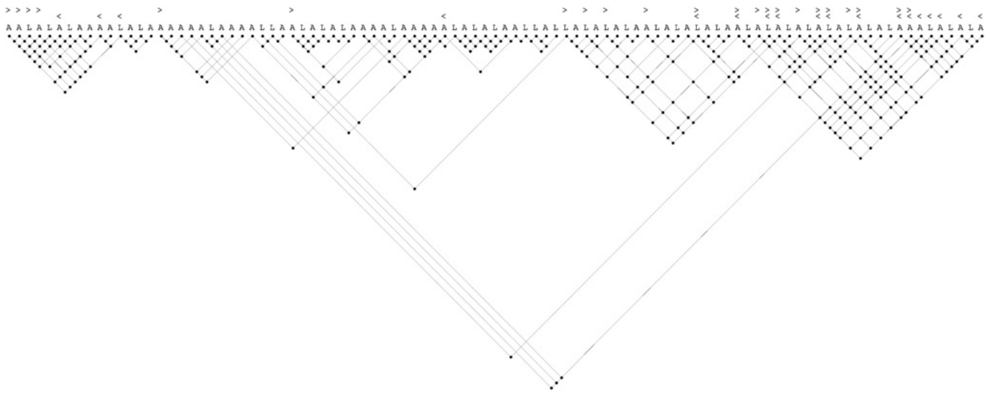


Figure 7 The linkograph of the first 6.5 min of NetMeeting session where 'A' represents the Architect and 'L' represents the Landscaper

NetMeeting session, but not in the face-to-face session. Overall the linkograph of the face-to-face session is more integrated than the NetMeeting session.

The link indexes of the face-to-face and the NetMeeting sessions are 3.05 and 2.88, respectively. Tables 2 and 3 record the critical moves and their percentages over the total number of moves (%CM) of the face-to-face session and the NetMeeting session, respectively. The face-to-face session has a total of 43.9% of critical moves with more than five links (%CM^5) which is marginally higher than the NetMeeting session which has a total of 41.2 %CM^5. From these figures the face-to-face session seems to be more productive than the NetMeeting session. However, the NetMeeting session has a higher %CM^7 than the face-to-face session, 28.9 against 20.4. Tables 4 and 5 show the break down of critical moves by individuals in the two sessions; the critical moves percentage of the total number of moves is in bracket. These correspond well with our analysis of the leadership role with the leaders possessing not only more moves but also higher %CM.

4 *Statistical description of linkography*

If we remove all the linking lines in the linkograph in Figure 1 and only consider the nodes but not the moves, we will get nodes in a two dimension space, Figure 8. 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 or the average position of all the nodes, and their deviations in the X and Y axes.

Table 2 Critical moves with more than five, six, and seven links of the face-to-face session

	CM^5 (%CM^5)	CM^6 (%CM^6)	CM^7 (%CM^7)
Forelinks	21 (21.4)	17 (17.3)	13 (13.3)
Backlinks	22 (22.4)	15 (15.3)	7 (7.1)
Total	43 (43.9)	32 (32.7)	20 (20.4)

The value inside the brackets shows the critical moves as percentage of total moves.

Table 3 Critical moves with more than five, six, and seven links of the NetMeeting session

	CM^5 ($\%CM^5$)	CM^6 ($\%CM^6$)	CM^7 ($\%CM^7$)
Forelinks	22 (22.7)	17 (17.5)	14 (14.4)
Backlinks	18 (18.6)	16 (16.5)	14 (14.4)
Total	40 (41.2)	33 (34.0)	28 (28.9)

The value inside the brackets shows the critical moves as percentage of total moves.

The total number of 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). Adding all the X coordinates of the nodes and dividing by the total number of nodes will give the mean value of X, which is the average location of the nodes in the X-axis. A higher mean value of X implies that more nodes appear at the end of a session and a lower value suggests that more nodes are present in the beginning of the session. In the same way, adding up the Y coordinates of the nodes and dividing by the total number of nodes will give the mean value of Y, which is the average location of the nodes in the Y-axis. 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 clustered around the means. The lower the value the closer those nodes are towards the mean. Tables 6 and 7 relate the appearance of linkographs, with the same number of nodes as Figure 1, to these statistical values. The figures in the two tables are exaggerated for illustration and may look unrealistic.

4.1 Face-to-face and NetMeeting session

Tables 8 and 9 show the statistical descriptions of the linkographs, in reference to the position of links, for the face-to-face and NetMeeting session, respectively. Figure 9(a) and (b) is the corresponding scatter plots.

The normalized saturation (link index) of the face-to-face and the NetMeeting sessions are 3.05 and 2.88, respectively. According to Goldschmidt the face-to-face session has a more productive design process because the face-to-face session has a slighter higher link index.

Table 4 Critical moves by individuals in the face-to-face session, with A and SA represent the Architect and Senior Architect, respectively

	CM^5		CM^6		CM^7	
	A (%)	SA (%)	A (%)	SA (%)	A (%)	SA (%)
Forelinks	7 (18.5)	14 (23.3)	6 (15.8)	11 (18.3)	4 (10.5)	9 (15.0)
Backlinks	7 (18.5)	15 (25.0)	5 (13.2)	10 (16.7)	1 (2.6)	7 (11.7)
Total	14 (36.8)	29 (48.3)	11 (28.9)	21 (35.0)	5 (13.2)	16 (26.7)

The value inside the brackets shows the critical moves as percentage of total moves.

Table 5 Critical moves by individuals in the NetMeeting session, with L and A represent the Landscaper and Architect, respectively

	CM^5		CM^6		CM^7	
	L (%)	A (%)	L (%)	A (%)	L (%)	A (%)
Forelinks	8 (21.6)	14 (23.3)	6 (16.2)	11 (18.3)	5 (13.5)	9 (15.0)
Backlinks	5 (13.4)	13 (21.7)	4 (10.8)	12 (20.0)	4 (10.8)	10 (16.7)
Total	13 (35.1)	27 (45.0)	10 (27.0)	23 (38.3)	9 (24.3)	19 (31.7)

The value inside the brackets shows the critical moves as percentage of total moves.

The NetMeeting session has a higher X-mean and a higher standard deviation than the face-to-face session. This indicates, in general, that the links in the NetMeeting session are distributed more towards the end of the session compared to the face-to-face session. This corresponds to the qualitative analysis of the NetMeeting session, where we see numerous actions occurring in the last 1.5 min. The NetMeeting session also has a higher standard deviation indicating that the nodes are more dispersed than the face-to-face session. This also matches our qualitative understanding because at the beginning of the NetMeeting session the designers were trying to figure out how to scale in the shared whiteboard which formed a separate chunk at the beginning whereas in the face-to-face session we do not observe this kind of separated chunk.

For the mean values of Y, the face-to-face session has a higher value suggesting that the face-to-face session has links that are further apart, that is, longer links than the NetMeeting session. Also, the face-to-face session has a higher standard deviation which suggests more mixture of long and short links. This agrees with our qualitative analysis since in the face-to-face session, the designers referred to and traced over their drawing often causing these long links.

4.2 Cluster analysis of linkography

As we can see in Tables 2 and 3, and in Figure 9 the nodes in a linkograph may form clusters. In this section we explore the use of cluster analysis with the two case studies.

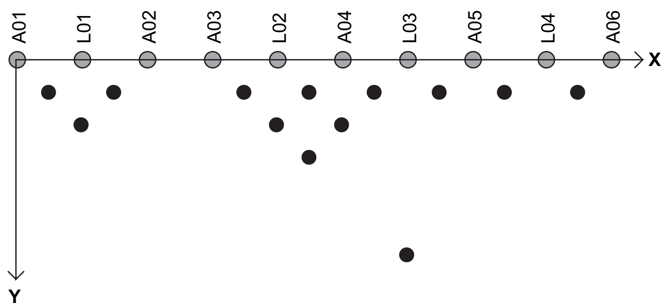
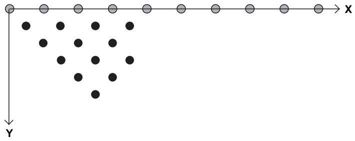
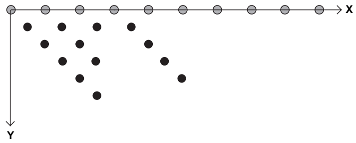
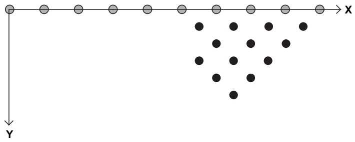
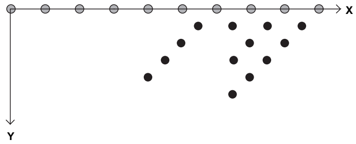


Figure 8 Reducing the graphical links to nodes in a two dimension space

Table 6 The shape of a linkograph, with the same number of nodes, in relation to mean and standard deviation of *X*

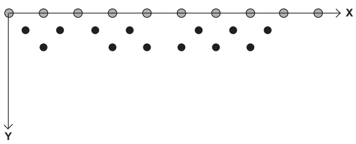
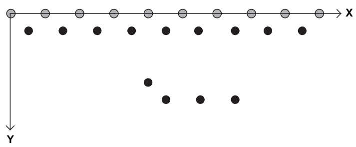
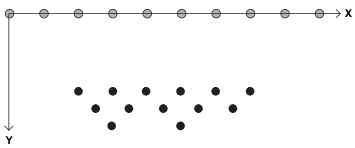
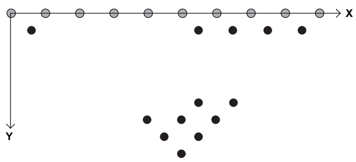
X-Axis	Small standard deviation	Large standard deviation
Small mean		
Large mean		

A higher value of *X*-mean signifies there are more activities at the end of the session.

4.2.1 TwoStep cluster

The SPSS TwoStep cluster algorithm 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* and *Y* variables were treated as continuous and Euclidean distance was used to compute the distance among

Table 7 The shape of a linkograph, with the same number of nodes, in relation to mean and standard deviation of *Y*

Y-Axis	Small standard deviation	Large standard deviation
Small mean		
Large mean		

A lower value of *Y*-mean indicates shorter linking distance.

Table 8 Descriptive statistics of the face-to-face session with 299 links

	Minimum	Maximum	Mean	σ
X Location	1.50	97.50	48.23	21.81
Y Location	0.50	38.50	3.97	5.10

clusters. Akaike's information criterion (Akaike, 1973), based on the maximum likelihood principle, was used for determining the number of clusters. Tables 10 and 11 show the result and Figures 10 and 12 are the scatter plots of Case I (face-to-face) and Case II (NetMeeeting), respectively.

4.3 Case I: face-to-face

4.3.1 Results and discussion

Figure 11 shows the variations within clusters, showing that Cluster 4 is different. In Figure 10, Cluster 4 seems to be the outlier, in statistic term. Neglecting this cluster for this moment, Clusters 1, 2 and 3 map well with the qualitative analysis. In Cluster 1 the two designers were discussing issues arising from the previous meeting. In Cluster 2 the Senior Architect started drawing and they were considering the behavioural impact of moving the lift, void, and bridge. In Cluster 3 the Senior Architect realized another issue induced by the setting back of columns. Cluster 4, being the statistical outlier, groups those links that are far apart which link Cluster 3 with Cluster 2 and Cluster 1. In this particular case, the links were formed either because the participants were tracing over or referring to depictions that they drew earlier or when they were concerned with the symmetrical axis of the building.

4.4 Case II: NetMeeting

4.4.1 Results and discussion

Again, neglecting the statistical outlier, Cluster 5, the other clusters reflect the themes of the protocol. Readers should note that the cluster numbers here do not reflect the time sequence, the time sequence would be Cluster 1, Cluster 2, Cluster 4, and then Cluster 3. In Cluster 1 they were discussing constraints imposed by NetMeeting – how to scale without references. Cluster 2 began with the Architect reading from the brief and continued with the concerns regarding the functional spaces and their relationships. In Cluster 4 the Landscaper introduced another idea suggesting they take advantage of the level changes in the site which lead to further development by the Architect in Cluster 3. Cluster 5, the statistical outlier, contains the links between this development and the functions in Cluster 2. The Architect was referring to his interpretation

Table 9 Descriptive statistics of the NetMeeting session with 279 links

	Minimum	Maximum	Mean	σ
X Location	1.50	96.50	57.83	29.85
Y Location	0.5	34.50	3.60	4.61

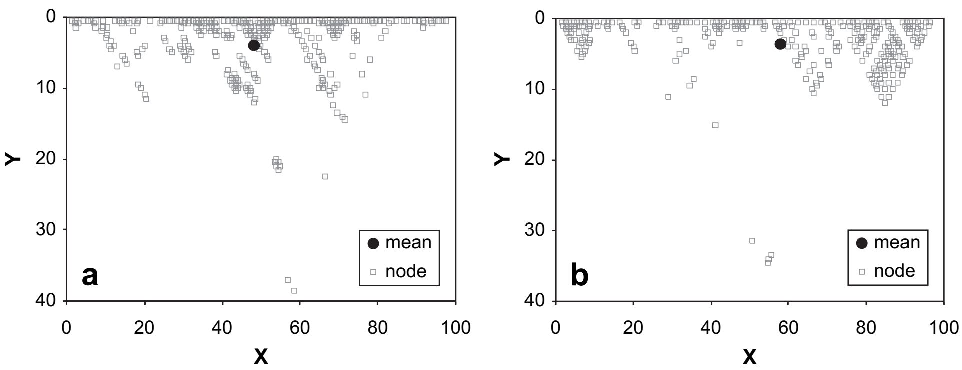


Figure 9 (a) Scatter plot of the face-to-face session, (b) scatter plot of the NetMeeting session

of the brief when proposing the location of these functional spaces. Figure 13 shows the variations within clusters. The mean value of Y slightly increases towards the end of the session indicating that links are getting longer.

5 Using entropy to interpret linkographs

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 in relation to the surprise it produces or the decrease in uncertainty. Given that event E1 has a lower probability than event E2, you would be more surprised if E1 had occurred, hence you get more information. For example, I randomly pick 13 cards out of a standard 52-card pack; you will be very surprised if I tell you I had a full suit of spades. By this unitary communication you know all the cards I am holding. Using this relation of probability of outcome and its information carried, Shannon devised an information-generating function $h(p)$ such that:

$h(p)$ is continuous for $0 \leq p \leq 1$,
$h(p_i) = \text{infinity}$ if $p_i = 0$,
$h(p_i) = 0$ if $p_i = 1$,

Table 10 Centroids of the Case I (face-to-face) clusters

Cluster	X		Y	
	Mean	Standard deviation	Mean	Standard deviation
1	14.18	6.97	2.82	2.95
2	42.50	7.42	3.56	3.29
3	71.67	10.11	3.27	3.72
4	56.39	4.12	24.72	7.43
Combined	48.23	21.81	3.97	5.10

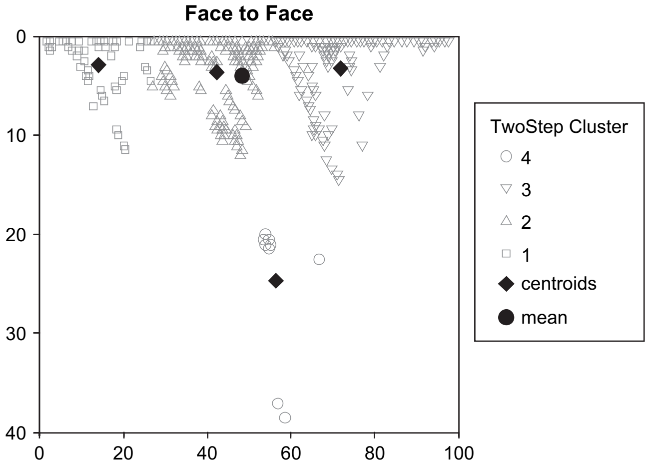


Figure 10 Scatter plot of the clusters of Case I, face-to-face session

$h(p_i) > h(p_j)$ if $p_j > p_i$,
$h(p_i) + h(p_j) = h(p_i \times p_j)$ if the two states are independent.

Where p is the probability, p_i is the probability of state i, and p_j is the probability of state j.

It was proved that the only function that satisfies the above five properties is

$$h(p) = -\log(p). \tag{1}$$

The entropy H, the average information per symbol in a set of symbols with *a priori* probabilities, is expressed in formula (2):

$$H = p_1 \times h(p_1) + p_2 \times h(p_2) + \cdots + p_n \times h(p_n) \tag{2}$$

where $p_1,\ldots p_N$ are probabilities corresponding to $S_1,\ldots S_n$ states.

Substitute formula (1) into formula (2) we get:

$$H = -\sum_{i=1}^{n} p_i \log(p_i) \quad \text{with} \quad \sum_{i=1}^{n} p_i = 1 \tag{3}$$

Table 11 Centroids of the Case II (NetMeeting) clusters

Cluster	*X*		*Y*	
	Mean	Standard deviation	Mean	Standard deviation
1	9.04	5.77	1.87	1.43
2	39.40	7.38	2.12	2.97
3	85.61	5.06	4.09	3.00
4	65.13	5.65	3.51	2.98
5	53.88	2.29	33.38	1.31
Combined	57.83	29.85	3.60	4.61

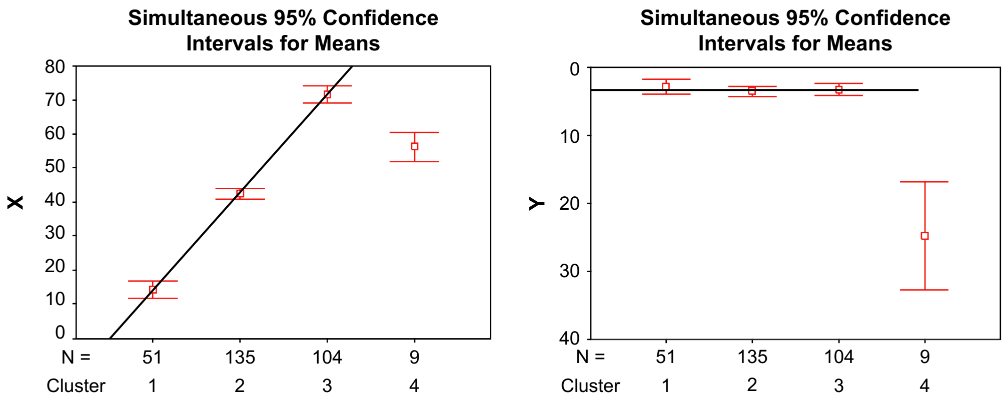


Figure 11 Within cluster variation for the face-to-face session

In this study we shall count entropy in rows of forelinks, backlinks, and link distance that will be denoted as 'horizonlinks', according to the ON/OFF of a link, Figure 14. 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 is not a link itself but it bears the notion of length of the links which is a measure of move-time (separation) between links. We can view it as a measure of the distances of the links. In Figure 14(c), we can observe there can be $n-1$ rows in an n moves linkograph. Let $n-i$ denotes the row number, the links in rows with a small i indicate that the distance between moves is small, we label them as short links. These moves will likely reside in working memory and we refer this to the cohesiveness of ideas. However, if the ideas are too cohesive, it might imply fixation and lack of innovation. The links in the rows with a large i connect moves that are far apart; we call them long links. These moves may not be in the working memory, we consider those as incubated moves. Long links are comparatively rare and may signify reflection in action. Our assumption of a good design process contains unsaturated short links plus a number of long links.

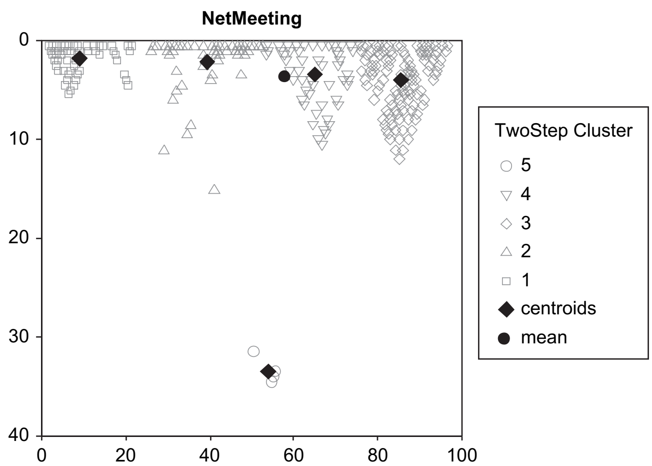


Figure 12 Scatter plot of the clustered of Case II, NetMeeting session

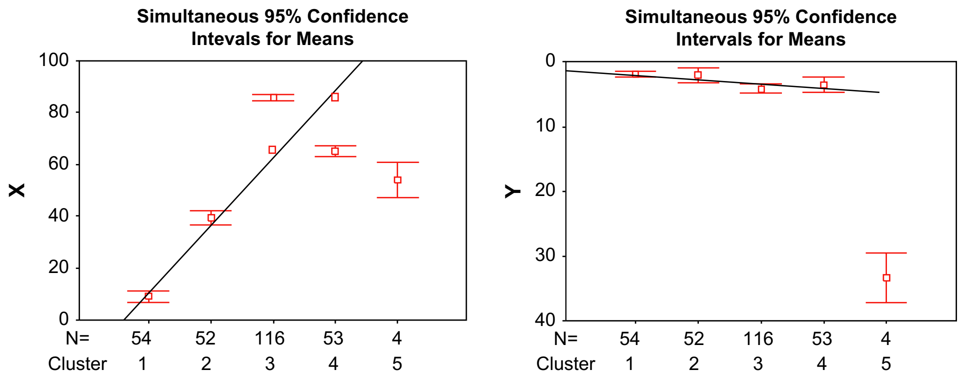


Figure 13 Within cluster variation for the NetMeeting session, squares were added to represent the clusters in the correct time sequence

Following Shannon's theory, formula (1), in each rows H becomes:

$$-p(\mathrm{ON})\log(p(\mathrm{ON}))-p(\mathrm{OFF})\log(p(\mathrm{OFF})) \quad \text{where } p(\mathrm{ON})+p(\mathrm{OFF})=1. \tag{4}$$

The maximum entropy (most random) of each row occurs when the ON/OFF of the links are most unpredictable, that is, half of the row are linked and half of it are un-linked. Figure 15 plots the value of H against formula (4).

The graph in Figure 15 is symmetrical, the slope of the graph decreases sharply as the probability moves away from 0 and 1. This indicates that when the links move away from the 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 a designated number of links) and a high value of link index, disregarding the total number of possible links, 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 are between 35 and 65% it will produce a very positive value (rich design process). If the links are less than 5% or over 95%, it will produce a very low H value (below 0.29).

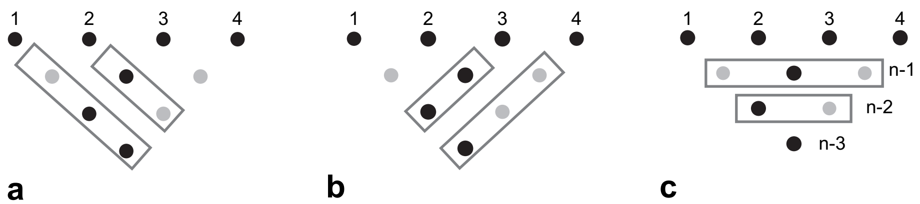


Figure 14 (a) Measuring entropy of forelinks of each row, (b) measuring entropy of backlinks of each row, and (c) measuring entropy of horizonlinks

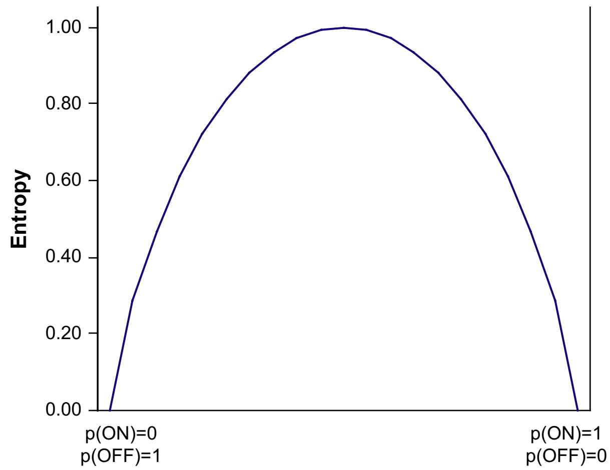


Figure 15 Maximum entropy when $p(ON) = p(OFF) = 0.5$

In practice it is unlikely to have a fully saturated linkograph that has more than seven moves. This also depends on the length of an episode; Figure 16 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 that people try to maintain a coherence of conversation/thought (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 row in a linkograph will seldom have more than nine links. Taking the 35% linkage as denominator, therefore, any rows with row length of more than 26 moves will not have a high H value.

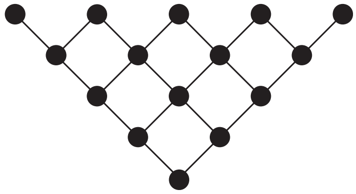
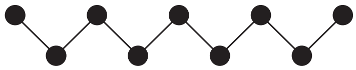
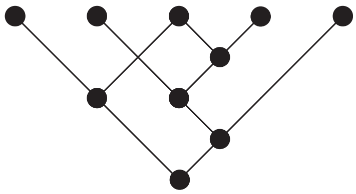
The hypothesis is that a higher entropy implies a process with more opportunities for idea development.

5.1 Hypothetical cases

Four hypothetical design scenarios with only five moves or four stages are used to examine these concepts further. Table 12 shows some possible linkographs together with an interpretation of the design process they reflect. Tables 13–15

Figure 16 Typical distributions of links in a linkography of a design process

Table 12 Some possible linkographs of five design moves and their interpretations

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

are the entropy, using formula (4), of the forelinks, backlinks, and horizonlinks, respectively. Table 16 is the cumulative entropy which maps well onto our understanding of those scenarios: Cases 1 and 2 receive zero entropy as they represent low opportunity for idea development, Case 3 has an entropy lower than Case 4 as Case 4 has a better integration among the moves.

Table 17 shows the link index and the critical moves (CMs) of the four hypothetical cases. There is no link in Case 1 so it does not have CM and has zero link index. Case 3 and 4 also do not have CM; Case 4 has a higher link index than Case 3 which indicates a better integration of ideas. For Case 2, it has the highest link index and CMs, so it should be the most productive scenario. However as explained in Table 8, this might not be the most desirable scenario.

Table 13 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 14 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	1.000	*2.918*

5.2 Entropy of face-to-face and NetMeeting sessions

Tables 18 and 19 show the entropy of the face-to-face and NetMeeting sessions, respectively. 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 incubation of ideas. In the face-to-face session the backlink entropy is slightly higher than the forelink entropy which might indicate higher opportunity of building upon than initiating moves. The NetMeeting session scored the opposite, which might indicate the initiation opportunity is higher than the response opportunity. These results tentatively match our qualitative analyses of both sessions. In the face-to-face session the designers were at 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. However, the differences in entropies are too small to be conclusive. 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 areas. This concurs with the link index study.

5.2.1 Role and participation of individuals

Tables 20 and 21 are 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

Table 15 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 16 Cumulative entropy of each case

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

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 a new idea – taking advantage of level changes which is an opportunistic initiation. The individuals' entropy scores faithfully reflect their opportunistic contributions. This contrasts the CM study in Tables 3 and 5 which show that the leaders in both sessions have higher %CM in both forelinks and backlinks.

6 Conclusion

In this study we explored design sessions where designers were working together on the same artefacts simultaneously. We proposed methods to acquire information from linkographs and tested them with two case studies. Standard descriptive statistics were able to describe the shape of a linkograph and in our case studies they were able to pick up some of the differences in the design processes such as the lengths of the links and the position of intensive activities.

The preliminary results using clustering and entropy were promising. We were able to map the clusters onto the actual design activities, and hence were able to label the semantics of a cluster. The statistic outliers contained long links that connect other clusters.

The traditional study of linkographs uses link index and critical moves to benchmark the productivity of a design session. We put forward that link index might bias towards saturated linkographs. Usually, this would not create any problems as most of the linkographs with reasonable moves would have relatively sparse links. Entropy, based on the information theory, captured another aspect of the linkograph which it biased towards half saturated linkographs. In the two case studies, the total cumulative entropies agreed with the link index with a different magnitude. We anticipated that entropy measures the idea development opportunities. Forelink entropy measures the idea generation opportunities in terms of new creations or initiations.

Table 17 Link index and critical moves of the four cases

	Case 1	Case 2	Case 3	Case 4
Link index	0	2	0.8	1
CM^3	0	2	0	0
CM^4	0	2	0	0

Table 18 Entropy of face-to-face session

Forelinks total *H*	Backlinks total *H*	Horizonlinks total *H*	Cumulative total
34.171	36.693	12.244	*83.109*

Table 19 Entropy of the NetMeeting session

Forelinks total *H*	Backlinks total *H*	Horizonlinks total *H*	Cumulative total
27.865	26.922	11.477	*66.264*

Table 20 Forelink and backlink entropy by the Senior Architect and the Architect in the face-to-face session

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

Table 21 Forelink and backlink entropy by the Architect and the Landscaper in the NetMeeting session

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

Backlink entropy measures the opportunities according to enhancements or responses. Horizonlink entropy measures the opportunities relating to cohesiveness and incubation. The differences between forelink and backlink entropies in both sessions were too small to draw solid conclusion. In the study of individuals' entropy contribution, it seems to reflect the opportunistic contributions of individual participants which is not shown in the critical moves analysis.

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