CAN ENTROPY INDICATE THE RICHNESS OF IDEA GENERATION IN TEAM DESIGNING?

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Abstract. This paper presents the development of a quantitative method to study team designing processes. It revisits *linkograhy*—a graphical representation of the design moves—and depicts ways of interpreting the linkography using *entropy* from Shannon's information theory, to compare design processes. A case study with two different scenarios is presented followed by the results and conclusions.

1. Background

Designers increasingly work across geographically distant locations. One of the reasons designers collaborate is because it provides an environment for idea generation. However, despite modern technologies, face-to-face interaction remains one of the most important elements in developing ideas (Salter and Gann, 2002). Computer tools mostly support the documentation and file sharing aspects of collaborative design activities. In order to develop tools that support the process of distant collaboration, a closer look at how design teams generate ideas is required as we currently have insufficient knowledge about these activities.

2. Linkography

Linkography has been used for investigating the structure of design idea generation processes and for comparing design productivity (Goldschmidt, 1990; Goldschmidt, 1995; Van der Lugt, 2003). It is a graphical representation of design processes in terms of the links between design moves. A design move was described by Goldschmidt as an act that transforms the design situation, like a chess move. Design moves are usually abstracted from the verbal protocol and the links are established by discerning, using common sense, if a move is connected to the previous moves; this is illustrated in the following example of an architect (A) and a landscape designer (L) collaborating through the Internet (NetMeeting) with a shared whiteboard using tangible interfaces in an experimental setting. The design problem was a conceptual development of an art gallery in a triangle site adjacent to shore

with level changes. Table 1 is an extract from the transcript. Each utterance is tagged sequentially as a design move, A01 is the first move by the architect and L01 is the first move by the landscaper.

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 means I've to draw.

L01, *"for the gallery spaces", was a response to A's move in A01, "the north is up the page, so the best sun is down the page"*, therefore A01 and L01 are linked. However, when A asked L whether she saw his mouse, this move was not related to earlier moves so there was no link between A03 to the pervious moves. Figure 1 shows the linkography of the above transcription.

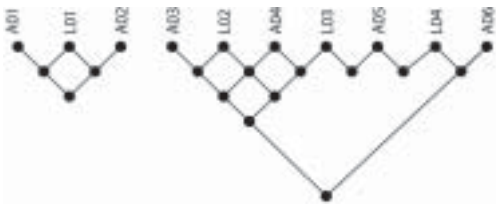


Figure 1. The linkography corresponding to the transcript in Table 1.

2.1. DESIGN MOVES AND DESIGN IDEAS GENERATION

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. In this study design moves are considered to be the externalization of the mental processes.

So to investigate design ideas generation is to study the design moves which can be observed and abstracted from verbal and video data. The collective moves can be seen as the clustering of ideas. In Goldschmidt's linkography, design moves were derived from verbal data using the turn taking of conversation as an indicator of the next move, other activities were consulted but not coded. Another approach is to code all non-verbal events that trigger moves, such as drawing, gesturing, etc. However, since most of these moves happened either simultaneously or in parallel with the conversation, it makes sense to group some of those with the verbal protocol. Table 2 shows some examples.

TABLE 2. Combine physical actions—in italica—with verbal moves

A01	*Looking at brief*
A02	The north is up the page, *(Start looking at display)* so the best sun is down the page

2.2. DESCRIPTION OF LINKOGRAPHY

To illustrate how linkography can be used to represent design process, a hypothetical design process with only four moves or four stages is being considered. Table 3 shows some of the possible linkographs together with the interpretation of the design process.

TABLE 3. Some possible linkographs of four design moves and their interpretations.

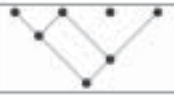
	Four moves are totally unrelated; indicating that ideas are not converging in this process, and is not a rich process
	All moves are interconnected, this shows that this is a total integrated process with no diversification, hinting that a pre-mature crystallization or fixation of one idea may have occurred.
	Moves are related only to the last one. This indicates the process is progressing but not developing
	Move 3 is not related to the others. There is a central idea and also one diversifying idea suggesting the process has a theme but is not monotonic. This we consider as a rich idea generation process.

Table 3 depicts only four cases of a four-states linkography. What are the possible combinations? By induction it can be shown that for an N state linkograph the possible combinations is given by

$$\prod_{i=2}^{N}({}_{i}C_{2}+1) \text{ where } {}_{N}C_{r}=\frac{n!}{r!(n-r)!} \text{ and } n!=n\times(n-1)\times\ldots\times 2\times 1 \qquad (1)$$

As N grows, the size of the possible linkography grows dramatically, that makes interpretation increasingly difficult. Goldschmidt (1996) used link index (the number of links relative to the number of moves) as an indicator of the 'strength' or 'productivity' of the design process. She also used critical moves (moves with intensive links) and critical path (sequence of critical moves) to compare different design process quantitatively. High values of link index and critical moves suggest productivity. This next section explores another method, the use of information theory, to analyze linkographs.

3. 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 X has a lower probability than event Y, I should be more surprised if X 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

$$\mathbf{H} = {}_{p1}{*}h_{(p1)} + p_2{*}h_{(p2)} + \ldots + {}_{pN}{*}h_{(pN)} \quad (2)$$

Where ${}_{p1}, \ldots {}_{pN}$ are probabilities corresponding to $S_1, \ldots S_N$ states and h(p) is the information-generating function devised by Shannon which equals –logb(p)

$$\text{Therefore } \mathbf{H} = -\sum_{i=1}^{n} p_1 \log_b(p_1) \text{ with } \sum_{i=1}^{n} p_i = 1 \quad (3)$$

3.1. ENTROPY OF LINKOGRAPHY

In this paper we propose the use of entropy as an objective measure of the idea-generation processes. The hypothesis is that higher entropy reflects a richer idea generation process. Our assumptions about a rich idea-generation process are:

1. The structure of ideas is reasonably integrated and articulated.
2. There is a variety of moves.

In the four-states linkographs in Table 3, we may consider the set of symbols as the 4 elements: {f, S2-S1, S3-S1, S4-S1 }. The symbols are shown in Table 4.

TABLE 4. The symbols and used to represent linkograph.

		or				
Symbol	ϕ	ϕ	ϕ	S_2-S_1	S_3-S_1	S_4-S_1

The total number of nodes is 3+2+1 = 6 or n(n-1)/2. Assuming the percentage frequencies as a probability distribution we can calculate the entropy H. The results are presented in Table 5.

TABLE 5. Entropy of some cases of a 4-state linkography.

Cases	No. of ϕ frequency %	No. of S_2-S_1 frequency %	No. S_3-S_1 frequency %	No. S_4-S_1 frequency %	Entropy H
1:	6 100%	0 0%	0 0%	0 0%	**0**
2:	0 0%	3 50%	2 33.3%	1 16.7%	**1.459**
3:	3 50%	3 50%	0 0%	0 0%	**1**
4:	3 50%	1 16.7%	1 16.7%	1 16.7%	**1.792**

Entropy measures the amount of information; a low number indicates no surprise. In our calculation of the entropy of linkography, the number of symbols in the set depends on the number of states, so comparison should be of same number of the states or it needs to be normalised. For an N state linkography there are N symbols. If the linkography contains only one symbol (only in the case of all f) there is no surprise, hence 0 entropy. A mix of those symbols will give a high entropy. The cases above map well on to our understanding.

4. Case study

A face-to-face in situ design session is compared with the in vitro session depicted in Section 2. In the in situ session, two architects, one much more senior than another, revisited the relationship between vertical circulation and the void areas of a commercial building. To demonstrate the use of entropy we only compare the process of production of the first page of drawings.

4.1. QUALITATIVE OBSERVATIONS

In the face-to-face sessions, designers frequently used drawing and gesturing to communicate without explicit verbalizing, and nearly all verbal protocols were accompany with non-verbal moves; they referred to materials from previous designs; they drew different diagrams separately, plan and section, and referred back and forth to the main plan drawing; actions were occurring spontaneously and in parallel. The generation of ideas and clarification of ideas happened simultaneously with numerous gestures mimicking the spaces of the design. There were interruptions such as phone calls for about a minute and the setting up of the microphone for recording. The designers were dealing more with the structural aspect or formal aspect in this session, while in the NetMeeting session they were focusing more on the functional or conceptual aspect of the design with time spent on studying the brief. Leadership roles can be observed in both sessions. In the NetMeeting session interactions were more sequential and consisted of more affirmations as compared to the face-to-face session and there was not much gesturing. There was more interaction among ideas, drawings, gestures, and verbal communications in the face-to-face session.

4.2. LINKOGRAPHS AND ENTROPY OF THE TWO SESSIONS

There were 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 2 and 3 show the linkograph of the sessions. The resulting entropy of the face-to-face session is 0.648 and the entropy of the NetMeeting session is 0.345. These correspond to our qualitative observations of the behaviour in the sessions in that the face-to-face session had much more idea generation and much more capacity for information to be presented and used.

Figure 2. The linkograph of the first 10.5 minutes of the in situ face-to-face session, H=0.648.

Figure 3. The linkograph of the first 6.5 minutes of NetMeeting session, H=0.345.

5. Conclusions

This paper has outlined a method to benchmark the idea-generation process during team design activities. Ideas are observed through design moves, the basic units that build up the design represented in a graphical form called linkograph with links between related moves. Design moves can take form in speech, drawing, annotation, and gesture. Entropy was introduced to measure the linkograph; a higher entropy represents a richer session, this was demonstrated by a case study and some elementary cases. These preliminary findings need to be validated with a larger case study.

In addition to determining the entropy of a portion of the session, using number of pages of drawing as segments, it is possible to calculate the entropy of the entire session; or to segment the session based on other criteria, such as time, and calculate and then compare the entropy of the different segments.

This approach forms the basis of a new tool to assess designer behaviour and provides 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.

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