Linkography for evaluating ideas connectivity of Computer Aided Design-based protocols

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This paper presents the analysis of four design protocols, using linkography, to characterise participants' design interaction and activity while designing with CAAD programs. The participants were final year students, who have spent at least four years in a school of architecture and were confident CAAD users. The conceptual structure and linkability of ideas was assessed using the Linkography method. The findings demonstrated that, for the same design problem, the conceptual structure and linkability of ideas can be assessed using the Linkography method. Furthermore, what characterised the continuity of CAAD design protocols is the number of ideas in association with design moves along the timeline of the design process.

Keywords: Linkography, Conceptual phase, Design process, Ideas connectedness, CAAD

BACKGROUND
Design cognition studies claim that Computer Aided Architectural Design (CAAD) is inappropriate for conceptual design and using it would restrain conceptual design. These claims were based on interacting with either sketching only or switching between sketching and CAAD; these studies employed design protocols analysis. However, most of these studies did not examine CAAD actively in the same way as it recorded sketching.

In comparison to other CAAD oriented studies within the studio context, one of the emphasised impacts of CAAD on the design process of the macro level of participants' interaction is efficiency and productivity. This suggests that what is actually happening during a design activity on the macro level of interaction is different from what is experienced on the micro level of design activity interaction in the cognitive studies, which is mainly considered "block of thought" (Tang 2001) and time consuming (Bilda and Demirkan 2003).

Design protocol provides a focused investigation on the design activity (van Someren, Barnard and Sandberg 1994) that may occur between a student and the CAAD, therefore, a pragmatic investigation (Creswell 2009) into the influence of CAAD on design activity and thinking aspects is still lacking. This study presents the linkographic analysis of four computer aided design protocols (for a comprehensive review on the design protocol study one may refer to the main research project by Salman, Laing, and Conniff 2014). This study aims to provide a structured analysis of ideas development through ideas connectedness along the design process. The following re-
search questions were inquired:

- Does using CAAD appear to affect the design process productivity and continuity in terms of ideas association and links?
- Is it a linked process or fragmented, and if so why?
- What association can the ideas that were expressed during the protocol have?
- What are the qualitative and quantitative differences between the selected protocols?

**RESEARCH METHODOLOGY**

Design protocol encoding can be approached from a different analytical perspective to code the conceptual dependencies between design ideas. From the work of Mazijoglou, Scrivener and Clark (1996) on structuring drawing development, alongside the sequential relationship between a given - former drawing and the later drawing, there is a reference to the development of this drawing and its refinement. At the same time, the drawing transition network represents the flow of movements between drawings during the design sessions (Mazijoglou, Scrivener and Clark 1996). Again, this flow of conceptual-perceptual movements could be traced within the session's linkograph. Linkography is a graphical structure that retains the conceptual-perceptual relations between "design moves" (Goldschmidt 1995, 1997, 2003) or "design ideas" (van der Lugt 2000; Bilda 2006; Bilda and Gero 2008). Goldschmidt defines a design "move" as: "an act of reasoning that presents a coherent proposition pertaining to an entity that is being designed" (Goldschmidt 1994), or "a step, an act, an operation, which transforms the design situation relative to the state in which it was prior to that move" (Goldschmidt 1997). The developmental aspect of structuring the drawing into a network is to some extent related to Goel's notion of transformative conception of refinement and development, which was utilised recently by Cai, Do and Zimring (2010) to investigate the impact of precedents on design and on the micro level of the design process.

**ANALYSIS**

In the current study, a design move is determined by any action that has changed the status of the design into a new status that can be traced externally. Those actions could be decisions, goals, constraints that were set and met successfully. The protocol segments were the main unit for coding design moves. But the segments included more information that a design move would entitle. Assigning design moves was based on Goldschmidt's (1995) definition of a design move. Design moves were assigned by considering the visual and verbal context of every segment, emphasising the context of its being and its potential connectedness along the design process. Most of the segments though revealed one to two design moves at the most, Figure 1. A design move then became equal to an idea that had been externalised verbally or graphically during the process.

![Figure 1](taken from S4 linkograph)

Although Goldschmidt stressed common sense as the main approach to determining the link between two or more design moves, she mentions that this, in practice, means that: "...a link between two moves is established when the two moves pertain to the same, or closely related, subject matter(s)..." Other linkographic studies have shown that utilising common sense seems to be a tentative technique to elicit the relations of latter/former moves. Other researchers like van der Lugt (2000) have strengthened Goldschmidt's notion by defining indicators for judging the commonality between design moves. He suggested that the common sense reliability could be
enhanced by developing indicators for links; in addition to the similarities in content (Bilda 2006) and argued that "a link is present, even though the subject matter between these two ideas is not closely related". Also by associating links, the potential contribution of every move along the design process (line) is decided against all the other moves that have been assigned as design moves.

However, there are two difficulties in associating the links along the design timeline. The first one is how to track the content of each move (each segment could have more than one sentence) and the other difficulty relies in the association between links that occur further down the line of the design. To overcome these difficulties Bilda (2006) has suggested a means to aid the analyst’s common sense, by employing a word search to find any commonality in meaning of such distinct design moves. This includes more than one run through the questionable segments and links.

The coded links are categorised into fore-links and back-links. Each has a different meaning with regard to the design process. Back-links are links that are related and considered as a concluding move "that summarises or evaluates points raised in the exploration" (Goldschmidt 1995), and Fore-links "record the path that led to a move's generation, while fore-links bear evidence to its contribution to the production of further moves" (Goldschmidt 1995). The total number of back-links and fore-links are equal in every linkograph but different on the level of a design move, Figure 2.

Researchers such as Goldschmidt (2003), Bilda and Gero (2008) and Van der Lugt (2000) devised a number of measures for evaluating (conceptual) productivity and design flow. This study also uses the same measures of critical moves, link index and clusters. Goldschmidt (2003) defines "critical move" (CM) "identifies design concepts that are deemed "successful" in the sense that the designer values them enough to devote time trying to develop the concepts or at least to promote them at various points in the protocol". CM percentage refers to the total number of CM in a design session in relation to total number of moves. Link Index (LI) is a measure of how connected the design ideas are in a design session. In order to calculate the link index in the overall session, the total number of links is divided by the total number of moves in the design session.

**Figure 2**
An example of coding the forelinks and backlinks of a design move.

**DESCRIPTIVE RESULTS**

Coding the design session in terms of design move(s) and moves association, has revealed the structure of the conceptual/visual association. Every participant has revealed a different visual pattern that is related directly to the design protocol data and the development of the student's ideas. As shown in Figures 3, 4, 5, and 6.

Examining the resulting linkographs showed many differences in the way the student’s ideas were connected during design. These differences are presented on two levels of analyses: the first level was carried out using the quantitative method, by which linkograph is quantified by a number of measures, that is number of moves, link index (LI), critical moves (CM), percentages and link clusters. The other level was the conceptual content of the process from a methodological point of view, where concept or a partial idea of a concept is forming along the design process timeline. With respect to content analysis, linkograph is seen as a structure of associations among the design moves, that is coding the relationship between any two dependant design moves.
Figure 3
S1 design protocol
Linkograph.

Figure 4
S2 design protocol
Linkograph.

Figure 5
S3 design protocol
Linkograph.

Figure 6
S4 design protocol
Linkograph.
QUANTITATIVE RESULTS

The design protocols are described quantitatively through linkographic measures of link indices (averages), critical moves (CM) and percentages. An average of fifty-three moves was decided by the students that created an average of 160 links among themselves in an average duration of 59 minutes. As shown in Table 1, the Link index for S1, S2, S3 and S4 are 3.1, 3.2, 2.8 and 3.1, respectively.

Table 1

<table>
<thead>
<tr>
<th>Cases</th>
<th>Duration (hr:mn:sec)</th>
<th>No. of moves</th>
<th>No. of Links</th>
<th>Link index</th>
<th>% CM5</th>
<th>% CM6</th>
<th>% CM7</th>
<th>% CM8</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>00:57:26</td>
<td>46</td>
<td>141</td>
<td>3.1</td>
<td>13</td>
<td>9</td>
<td>4</td>
<td>7</td>
</tr>
<tr>
<td>S2</td>
<td>00:46:18</td>
<td>60</td>
<td>160</td>
<td>3.2</td>
<td>19</td>
<td>7</td>
<td>7</td>
<td>5</td>
</tr>
<tr>
<td>S3</td>
<td>01:16:41</td>
<td>48</td>
<td>156</td>
<td>2.8</td>
<td>15</td>
<td>10</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>S4</td>
<td>00:56:55</td>
<td>60</td>
<td>166</td>
<td>3.1</td>
<td>10</td>
<td>5</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Av</td>
<td>00:56:00</td>
<td>53</td>
<td>155.5</td>
<td>2.9</td>
<td>15.3</td>
<td>8</td>
<td>4</td>
<td>4</td>
</tr>
</tbody>
</table>

S2 (multi CAAD programs) had the highest LI among other protocols. LI value was the same for S1 (single CAAD program protocol) and S4 (single CAAD program protocol), while S3 protocol had the smallest LI value. This means that S2 multi CAAD protocol is the most productive. This may suggest that switching between two programs may be better in terms of the content and the structure of a CAAD design process as he also solved the problem in 2D then 3D.

Design reasoning studies (e.g. Goldschmidt and Weil 1998) proved that structure and content correlate to one another. Accordingly, a productive move in a Linkograph spreads in two directions, therefore, identifying the critical moves (CMs) in terms of its conceptual connectivity describes design process advancement.

With respect to critical moves (CM) and percentages, CM is a move which has at least 3 links in one direction to 8 links. The threshold varies upon the research purpose and cases (Goldschmidt 2009 personal communication by email), therefore this was decided through the percentages of (CM5, CM6, CM7 and CM8), as shown in Figure 7.

The percentages of critical moves of five links, (either forward or backward CM5), was the highest percentage which ranged from 10% to 19%. Likewise,
CM5 percentage was the highest among other CMi for each student.

**LINK DENSITY IN CLUSTERS**

To examine the conceptual continuity in terms of the association of design ideas to reflect on the study question: What association can the ideas that were expressed during the protocol have? Cluster density was computed. A cluster in the design process (linkograph) means a successive number of design moves, more than three (Bilda and Gero 2008) that are linked and have a serial conceptual dependency. This reflects on the "suggestive" design moves of a design process, which is followed by a series of moves that explore issue(s) raised by the suggestive move (Goldschmidt 1995, 2003; Goldschmidt and Weill 1998; Dorst and Dijkhuis 1995) or the other related moves within that cluster (Bilda and Gero 2008). In other words, this means that the clusters refer to the evolution of a partial idea towards a tentative design. The number of design moves that form a cluster, define a cluster size. For example, if five consecutive links were in sequence then the cluster size is six, because six design moves formed five links cluster. These links spread to relate to other design moves along the process in both directions: forward and backwards. To know what type the cluster is, the links are counted in both directions to define whether the cluster is a forward or a backward one. According to Bilda and Gero (2008) this helps to know the density of a cluster by dividing the total number of links of a cluster on the size of a cluster.

The results of the total number of forward and backward link clusters, size of clusters, and link density in the clusters for all participants are shown in Table 2. Six clusters were identified in three of the linkographs of S1, S2 and S3, and seven clusters in S4 linkograph. The number of backward clusters in all the linkographs was higher than the forward clusters.

This suggests that CAAD affected the students in two ways: (1) made the students revise, evaluate and repeat their ideas more often than generate or propose, and (2) to an extent made the students less inventive in terms of the number of new ideas, however, the nature of the task and the time required to finish the experiment should be considered. These points agree with Goldschmidt's definition of the backward and the forward critical moves (1995). Another point to discuss is the observed positions of the two types of cluster. In each of the linkographs the first identified cluster was a forward cluster and the last two or three clusters were backward clusters. This suggests that most of the participants from the start of designing started to externalise their ideas, whether through CAAD or words to reach a tentative solution to the design problem. Also, it suggests that the initial ideas are deemed to be the most successful moves that a designer makes which enable the designers to further develop their earlier ideas.

In between the first and the end clusters there was no common pattern for all participants, but rather interplay between the two types. Two of the participants (S2 and S4) showed continuous behaviour in constructing forward ideas, the other two, S1 and S3, inverted their ideas backwards to what they proposed in the first cluster to improve and check for two successive clusters (no 2, 3). Then engaged in forward thinking (cluster 4), S4 showed a different pattern of continuous forward thinking and then spent the later 4 clusters in reverse thinking. This is shown in Figure 8.

![Table 2](image)

Clusters and density of links.
Figure 8
the types of the clusters in the same sequence of occurrence.

Coding the clusters with colours showed the crossover of clusters in the linkograph, mainly in the shape of triangles. This suggests that every cluster spreads in both directions to form a joint smaller pyramid and as a result, all clusters were interconnected. When the student is satisfied with the result he mostly inverts his thought backward to relate to earlier thoughts.

The average size of clusters was higher for the forward clusters compared to the backward clusters. It was also higher for all participants in the forward clusters except S3. It also shows that the fore-link density is relatively higher than back-link density; as it was higher for all participants except for S4. When the fore-link density is higher than the back-link density it means that the forward clusters initiated more ideas later on in the process (Bilda and Gero 2008). High density reflects rich idea development and that these ideas were potentially successful.

**DISCUSSION**

The number of coded moves was relatively lower compared to the initial number of segments. The difference implied that the segment includes a larger amount of information than a design move. This is due to the fact that when a segment is coded under the design micro strategy, the intention is one, for example proposing a solution, or evaluating a solution, where as this intention could include more than one idea or more than one design move (act that changes the design situation). For example, proposing a design solution could include one or two different ideas or developed ideas, especially when the segment was externalised verbally. Normally the student becomes more concise when externalising graphically, thus, the number of segments in the design processing coding scheme was higher than the number of design moves in the linkography-coding scheme.

Another observed feature is the qualitative meaning and extensiveness of the words used in the verbal subpart of the protocol. On the general level of design protocol and on the specific level of ideas connectedness, two aspects were observed. On the general level of protocols' transcriptions, words such as ‘maybe’, ‘probably’, ‘possibly’ and so on were used which reflect the ill defined nature of the design situation. On the specific level of ideas connectedness, another aspect of design moves' connectedness was revealed through tracing the common words between segments to see whether two distant moves were connected or not. This process revealed an interesting character within three of the analysed protocols (S1, S2 and S4). That is, some of the words used had become more extensive; the words (which have conceptual traces) that were verbalised during designing were changed into more inclusive and specific meaning along the timeline. This change is due to the change in the design status and design conceptual maturity, due to the evolving context of the design process. This was also traceable on the level of density clusters which appeared to confirm the conceptual progress, but mainly in forward moves and forward clusters.

**CAAD IMPACT ON IDEAS CONNECTIVITY**

Furthermore, Linkography analysis suggests that CAAD affected students' conceptual content in two ways: (1) participating students revised and repeated
their ideas more than proposed new or different ideas, and (2) for an extent made the students less inventive in terms of number of options, however, the nature of the task and the time required to finish the experiment should be considered. These points agree with Goldschmidt's definition of the backward and the forward critical moves (1995), and Bilda and Gero's (2008) definition of links density.

This suggests that from the start of designing, most of the participants started to externalise their ideas, whether through CAAD or words to reach a tentative solution to the design problem. Also, it suggests that the initial ideas are deemed to be the most successful, which are often revisited and developed. This is similar to designing under sketching conditions.

CONCLUSION

This study was an attempt to characterise participants' design thinking while designing with CAAD programs. The analysis represents four design protocols of final year students at a school of architecture. The protocols analysed varied in more than one aspect. This variation includes: (1) CAAD programs, (2) the mode of using CAAD programs whether single or multiple, (3) protocol segments (total number, duration and frequencies), and (4) design categories and total time spent in designing. This gave an updated insight into design thinking (process) while using CAAD programs in architectural design with final year participants. In light of the study results, the participants demonstrated that, for the same design problem (brief), restraining the conceptual design medium would not necessarily bind the participants to a certain design strategy or hamper the arrival at a tentative design regardless of its academic assessment. Instead, the conceptual structure and linkability of ideas was assessed using the Linkography method. Furthermore, what characterised the continuity of CAAD design protocols is the number of ideas in association with design moves along the timeline of the design process. The protocols were characterised by high linkographic measurements: Li, CM and Ld. However, the participant who used more than two software programs showed higher Li from the other linkographs. This characteristic alongside other results suggests that using more than one CAAD program may increase the connectedness of conceptual ideas along the design time line, and a higher number of forward clusters. Participants comments were positive about the design situation and the experiment. However, the ones who used CAAD early in design were regularly more positive about using CAAD in concept design. On the basis of these results, interacting with CAAD visual representations can be accepted as a conceptual medium and the use of CAAD alone for externalisation.

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