Chapter 6
Entropic Measurement and Design Outcome

This chapter presents an application of the entropic measurement of linkographs. Linkographs from the empirical protocol studies of six architects are used to verify whether the design outcome correlates with some entropy measure of the linkograph.

6.1 The Experiment

Again, Bilda's experimental data and link data (Bilda 2006) were used in this chapter. The aim of that research was to understand the role of imagery and sketching in the conceptual phase of the individual design process. Experiments with designing in a blindfolded condition (participants were not allowed to sketch during designing, only at the end of session) were set up for comparison with designing under normal (participants allowed to sketch) conditions. This chapter examines whether the differences in the design outcomes can be reflected in the entropic measures of their corresponding linkographs. Below is a summary of the experimental setup.

The six architects who participated (two females and four males) have each been practising for more than 15 years. Architects A1 and A2 run their own companies and have been awarded prizes for their designs in Australia; Architect A3 is a senior designer in a well-known architectural firm. These three participants were teaching part-time in design studios. A4 works for one of Australia's largest architectural companies and has been the leader of many residential building projects, from small to large scale. A5 is one of the founders and directors of an award-winning architectural company. A6 is a very famous residential architect in Sydney, and he directs his company, known by his name, with 50 employees. They all had experience with designing residential buildings.

Each architect was asked to participate in two design sessions; each lasted about 45 min, with at least 1-month's separation between them. They were asked to talk

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Fig. 6.1 **a** Blindfolded session followed by quick sketching, **b** sketching session (Bilda 2006)

aloud while designing and were tutored in doing so. In one session the designer was blindfolded (BF) during designing, so that s/he was unable to sketch, and then s/he was asked to quickly draw what s/he had designed at the end of the session with the blindfold taken off, as depicted in Fig. 6.1a. At least 1 month later, the same architect designed in their normal mode, that is, using sketching (SK), Fig. 6.1b. The same site was used, so the 1-month separation helped to minimise the possibility of familiarisation with the site if the sessions had been held closer together. Bilda (2006) did not explain the time separation in his thesis. Both sessions involved designing a house with different requirements, brief 01 and brief 02; site plan and site photos were provided. Design brief 01 required them to design a house for two artists: a painter and a dancer. The house was to have two studios, an observatory, a sculpture garden and living, eating, sleeping areas. Design brief 02 asked them to design a house, on the same site as design brief 01, for a couple with five children aged from 3 to 17, that would accommodate children's and parent's sleeping areas, family space, study, guest house, eating and outdoor playing spaces.

The sessions were video- and audio-recorded as raw protocol data. The participants were organised into two groups of three; the first group started with the BF session with brief 02, followed by the SK session with brief 01. In the second group the sequence was reversed and the briefs were swapped. This was undertaken to ensure the design outcomes were not biased by the brief or the sequence. Bilda (2006) did not explain the reversing of the sequences and the swapping of brief. The details of the experimental procedure can be found in Bilda (2006) or Bilda et al. (2006).

6.2 Design Outcome

In order to minimise subjectivity in the assessment, the design outcomes, sketches from the 12 design sessions, were double-blind reviewed by three judges (Amabile 1996). All the judges have practised and taught design for more than 15 years. They

Table 6.1 Cumulative score of the criteria in design sessions by three judges

	Innovative	Creative	Brief	Practical	Flexible	Average
BF01	4.0	5.3	7.7	7.7	6.0	6.1
BF02	4.3	6.0	6.3	7.0	6.3	6.0
BF03	6.0	6.3	7.7	7.0	7.3	6.9
BF04	5.0	5.7	7.5	6.7	5.7	6.1
BF05	6.3	7.3	8.0	7.7	6.0	7.1
BF06	4.3	3.7	5.7	5.0	5.7	4.9
SK01	4.3	5.0	6.3	6.0	5.3	5.4
SK02	5.3	5.7	6.3	5.7	6.3	5.9
SK03	6.7	7.3	6.3	5.3	6.7	6.5
SK04	4.3	4.7	5.0	3.7	4.0	4.3
SK05	6.0	6.3	7.0	7.0	5.7	6.4
SK06	4.0	4.7	5.3	5.7	5.0	4.9

were unaware of the experiment. The judges were given the design briefs and other materials. They were asked to assess the photocopies of the sketches according to five categories: innovation, creativity, satisfaction of the design brief, practicality and flexibility. A 10-point scale was used. Bilda (2006), using Kendall's coefficient testing, considered that the concordance between the three judges was sufficiently high to accept their scores as valid measures of the design outcomes.

Table 6.1 summarises the average score of the assessment criteria of the 12 design sessions, where the number following SK or BF is the designator of the particular designer. Examples of design outcomes are shown in Figs. 6.2 and 6.3. The following were observed:

1. the average score of the BF sessions was higher than the SK sessions;
2. all the BF sessions received higher scores than the corresponding SK sessions, with one exception that had an equal score (SK06 and BF06), the score difference ranged from 0.1 to 1.8;

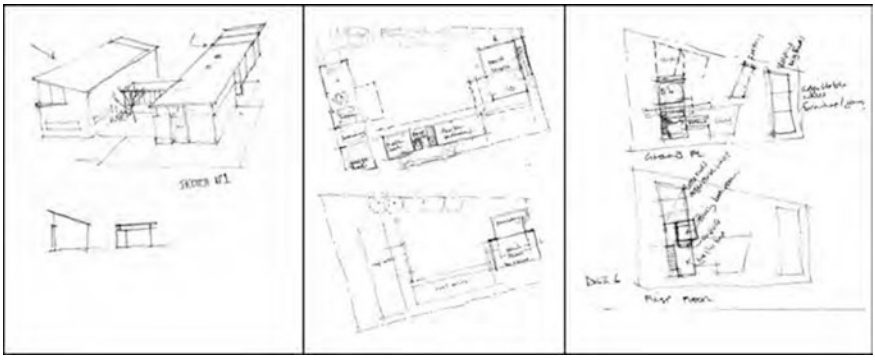

Fig. 6.2 Examples from high-scoring sessions, from left to right BF05, BF03, and SK03

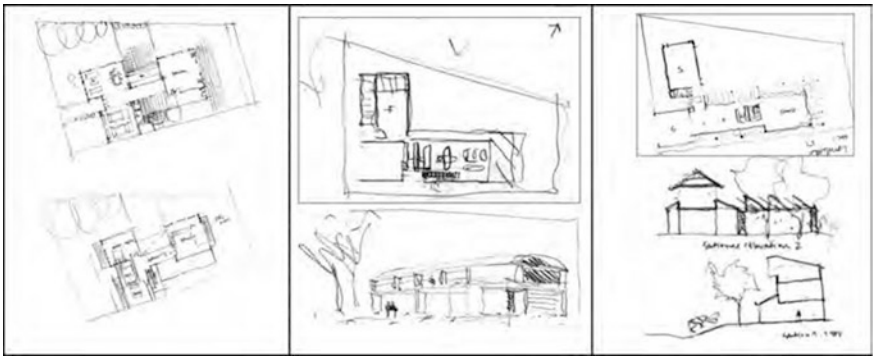

Fig. 6.3 Examples from low-scoring sessions, from left to right SK04, SK06, and BF06

3. the highest average score was 7.1 (BF05) and the lowest score was 4.9 (SK06);
4. adding the SK and BF scores showed that Architect 05 received the highest score and Architect 06 received the lowest score;
5. the scores for individual categories ranged from 3.7 to 8. There were two 3.7, the lowest, and three 4 s scattered in different categories. There were one 8 and four 7.7 s clustered around the blindfold sessions in the practical and satisfying the design brief categories.

Performing statistical testing (paired-*t* test) on observations 1 and 2 revealed that the score differences between the SK and BF sessions were not significant ($p = 0.068 > 0.05$).

6.3 High- and Low-Scoring Sessions

When the three highest-scoring and the three lowest-scoring sessions were grouped together, the score difference between them was over 40 %, which performing *t* test with unequal variance was found to be statistically significant ($p = 0.0014 < 0.05$). The innovative and creative categories were the main contributors to this score difference. The highest-scoring sessions were BF05, BF03 and SK03 and the lowest-scoring sessions were SK04, SK06 and BF06. Figures 6.2 and 6.3 show the sketches of the high and low scored sessions respectively. SK04, the lowest-scoring session, was considered the least "practical" and least "flexible" design solution. It also scored lowest in terms of fulfilling the design brief. BF06 was judged as the least "creative" design solution. At the other end, the high-scoring sessions, BF05 and SK03 were considered to be the most creative. BF05 scored highest in terms of fulfilling the design brief, and shared with one other session in being considered the most "practical" design.

6.3.1 *Qualitative Comparison of the Highest- and Lowest-Scoring Sessions*

In the lowest-scoring session, SK04, the designer started the session by analysing the site and considering the environment. Very early in the session the designer decided to have a two-level building (about 1 min 15 s into the session) near the south boundary. The designer then started laying out the spaces and writing down the requirements. On the ground floor, garage, living area, kitchen, bathroom, master bedroom, and laundry were considered in sequence. The location of the stairs was then positioned at around 9 min. The spaces were repositioned before considering the upstairs plan. Then the locations of bedrooms on the upper level were decided and a gallery link between them was proposed. The designer was not happy with the facade and decided "to reduce the amount of bulk on the top floor" (at around 18 min). The designer then checked whether all the spaces in the brief were being covered. In the remaining 28 min the designer mainly focused on relocating those spaces, changing the size and proportion of those spaces, and adding details. Some examples of verbal protocol are: "reduce those first two rooms slightly and enlarge the last one", "they were in the old positions and putting in the new positions", "should change proportions now". In this session, the designer spent a lot of time in the solution space, time was spent in solving problems created by having two storeys. The main idea seemed to be the central gallery, but it was not obvious in the drawings. Other ideas like privacy, light and views were considered but the final sketches bore no evidence of these.

In the highest-scoring session, BF05, the designer started commenting and analysing the requirements of the studio spaces. There were ideas of separating the dance studio from the painting studio, a courtyard between the studios, a long line of studio space, southern light for the painting studio, northern light versus southern light, borrowing a design from Glasgow Art School studio's ceiling with "big banks of south-facing light", and celebrating westerly light. Stacking up bedrooms or keeping them all single-storey were also considered. Afterwards, connections from the living area to the site were proposed. An "H" plan with two big "C" sections were considered. An open connection without roof was proposed. The following verbal protocol suggested, at around 19 min, that the designer had solidified those concepts and had a rough idea about the form: "So there's two forms, the big linear form of the dance studio spaces…". After that the designer worked on those details, such as "I am going to put a high wall on the southern side", decided how to enter the building and the levels of different spaces. Towards the end of the session a mental walk-through of the building was performed. This involved, for example, visualising the ceiling line and suggesting the location of the gutter. Finally, it was decided that the observatory should be in the courtyard, an outdoor space. The final sketches contained those design ideas that were observed in the verbal report, such as the "H" plan, the linear studios, the south-facing light, and the open connection.

6.4 Constructing Linkographs

According to Bilda (2006), the verbal protocols were segmented by inspecting the designer's intention, similar to the approach used by Suwa et al. (1998). Table 6.2 shows an excerpt from one of the protocols. The average segment length of the twelve sessions ranged from 17 to 26 s.

The links were constructed with the aid of searching for keywords and searching those keywords to find the segment. In the SK sessions, video footage was consulted, while in the BF sessions only verbal protocol was used to discern the links. Twelve linkographs were produced. Figures 6.4 and 6.5 represent the linkographs of the highest-scoring session and the lowest-scoring session respectively. Linkographs of all the sessions were documented in the Appendix D.

Table 6.2 An example segmentation of protocol

Time	Segment number	Segment content
15.50	51	Look, the thing that I'm thinking now is that because I've got such an overwhelming desire to design a courtyard house, and I think that in this kind of situation where you've got a very large site and, umm, a semi-public space that it can borrow, in a way, (16.07) that what you'd start to plumb for is a courtyard building; parts of which are built and parts of which are unbuilt
16.14	52	So, I'd be inclined to organise the dancer's studio and the living spaces and parts of the, the bedrooms… (16.29) or no, the bedroom spaces I think should go down to the east… to give them some separation…
16.34	53	So I'm imagining now a broken form, something that's got the courtyard essentially as its organising structure, but which then has parts built, parts unbuilt

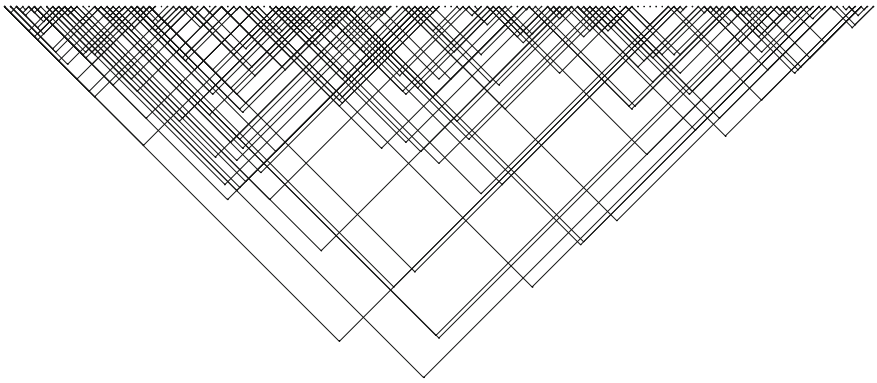

Fig. 6.4 The highest-scoring sessions

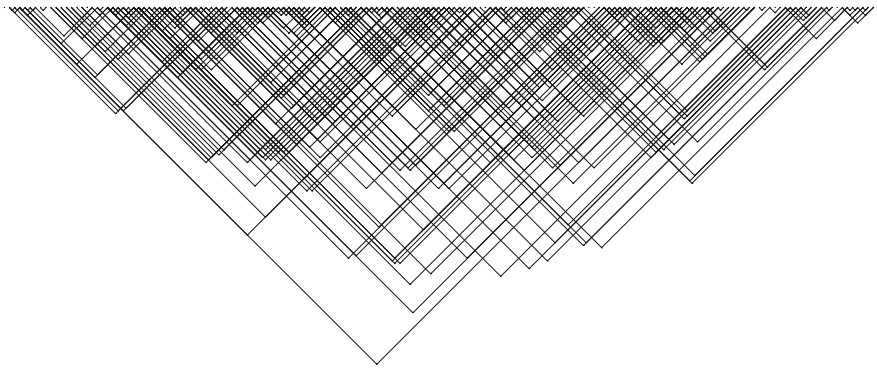

Fig. 6.5 The lowest-scoring sessions

6.5 Entropic Measurement

Table 6.3 shows the normalised entropy of each sessions together with their overall score. For ease of comparison, the normalised values were used: linkograph entropy divided by the number of moves, instead of absolute values.

Overall the BF sessions had higher entropy than their corresponding SK session, with one exception. The differences in entropy were marginal and the evidence was insufficient to suggest BF sessions had higher entropy than their corresponding SK session ($p = 0.14 > 0.05$ with paired t test). Positive correlation between entropy and the evaluation of the design outcome was weak. Some of the lowly ranked design sessions had high entropy values. The correlation coefficient r of the session's entropy and the corresponding outcome was −0.35. Therefore any hypothesis that the design outcome directly correlates with the entropy of the linkograph is not supported by the data from this study.

Table 6.3 Entropies of the 12 sessions

	nBH	nFH	nHH	Total	Outcome
BF01	0.125	0.122	0.060	0.307	6.1
BF02	0.161	0.155	0.066	0.383	6.0
BF03	0.143	0.140	0.055	0.338	6.9
BF04	0.240	0.220	0.093	0.553	6.1
BF05	0.224	0.193	0.082	0.499	7.1
BF06	0.188	0.189	0.105	0.481	4.9
SK01	0.137	0.124	0.077	0.337	5.4
SK02	0.157	0.150	0.065	0.373	5.9
SK03	0.124	0.131	0.044	0.299	6.5
SK04	0.227	0.203	0.098	0.529	4.3
SK05	0.176	0.125	0.071	0.372	6.4
SK06	0.184	0.175	0.063	0.422	4.9

nBH: normalised backlink entropy
nFH: normalised forelink entropy nHH: normalised horizonlink entropy

Table 6.4 Entropies of the high- and low-scoring session

	Session	Score	Entropy per segment
High score	BF05	7.1	0.499
	BF03	6.9	0.338
	SK03	6.5	0.299
Low score	SK04	4.3	0.529
	BF06	4.9	0.481
	SK06	4.9	0.422

6.5.1 Entropy of High- and Low-Scoring Sessions

Table 6.4 shows the scores and normalised total entropies of the three high- scoring and the three low-scoring outcomes of sessions in the descending order of entropy in its own category. The entropies of the high-scoring sessions correlated with the design outcome ($r = 0.86$) but the low-scoring sessions negatively correlated with the outcome ($r = -0.83$). The correlation coefficient is for reference only because the sample size is too small to be conclusive. The low-scoring sessions have higher entropies than the high-scoring sessions, which indicate more links among moves. This suggested that more links in the design process does not necessarily produce better designs. The design outcomes have been shown in Figs. 6.2 and 6.3.

6.6 Entropic Variations

In Sect. 5.4.3 it was suggested that the entropic variation and the rate of variation in entropy can be seen as the signature of a design session. In this section the three highest-scoring and the three lowest-scoring sessions were selected to be studied, because their score differences gave grounds for comparison.

6.6.1 Entropic Variation Graphs

Using a 28-move window, as described in Sect. 5.4.3, the changes in entropy graphs for the high-scoring sessions were plotted, as illustrated in Figs. 6.6, 6.7, and 6.8. The entropy dropped in the middle and increased toward the end. Figures 6.9, 6.10 and 6.11 show the second-degree polynomial fit of Figs. 6.6, 6.7 and 6.8 respectively. The entropy in a given window will be highest when the links are most random, that is, half linked and half unlinked. Full links or empty links will result in zero entropy, so there are two reasons for an entropy drop: saturation of links or sparsity of links. Reviewing the linkographs, all could be attributed to the second reason. So for the high-scoring sessions, the beginning and the end contained more links within the 28-move window.

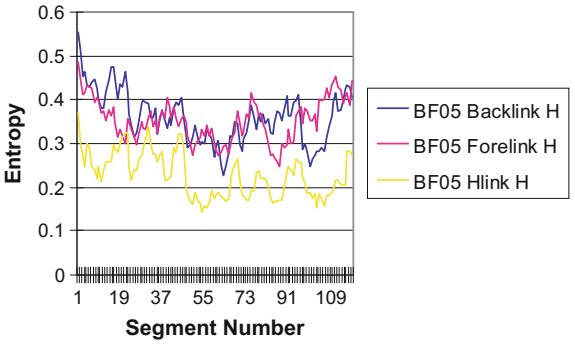

Fig. 6.6 Entropy variations in design session BF05 with total score of 7.1

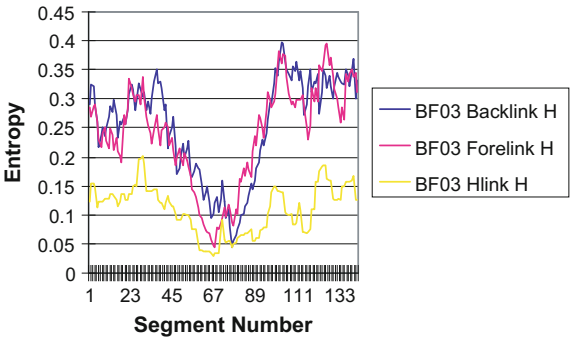

Fig. 6.7 Entropy variations in design session BF03 with total score of 6.9

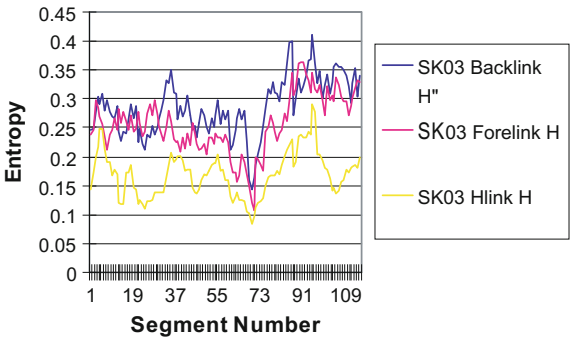

Fig. 6.8 Entropy variations in design session SK03 with total score of 6.5

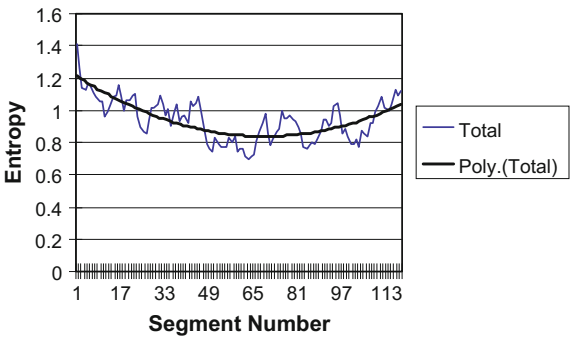

Fig. 6.9 Quadratic fit of entropy variation in design session BF05

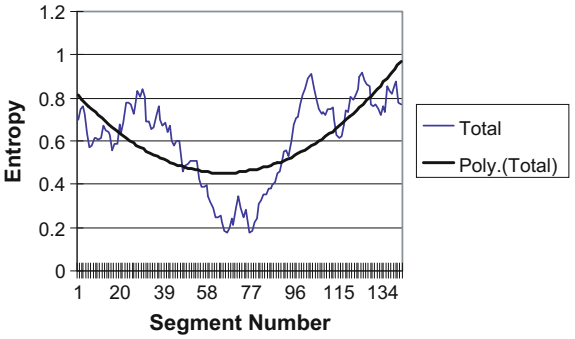

Fig. 6.10 Quadratic fit of entropy variation in design session BF03

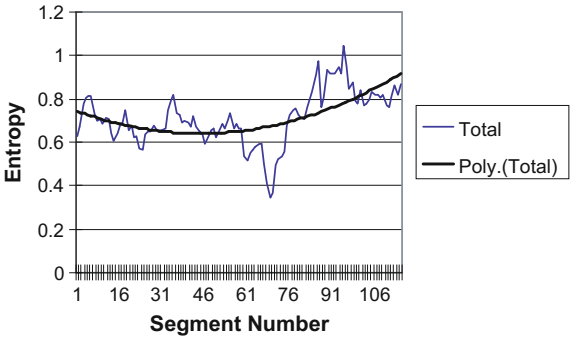

Fig. 6.11 Quadratic fit of entropy variation in design session SK03

Figures 6.12, 6.13 and 6.14 are the plots of the entropy variations in the low-scoring sessions. Figures 6.15, 6.16 and 6.17 show the second-degree polynomial fit of Figs. 6.12, 6.13 and 6.14 respectively. The curvature of the polynomials were opposite to the high-scoring session, at the beginning and towards the end there were less saturation of links within the 28-move window, which meant less coherence of ideas at the beginning and end of the session.

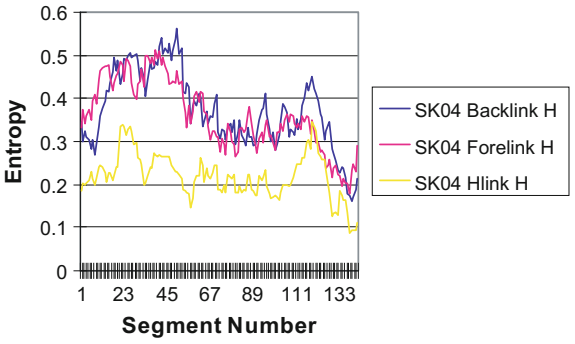

Fig. 6.12 Entropy variation in design session SK04 with total score of 4.3

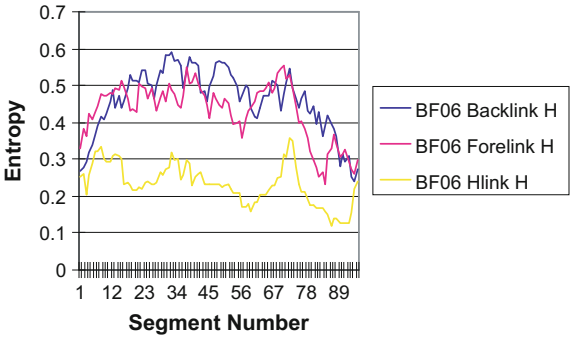

Fig. 6.13 Entropy variation in design session BF06 with total score of 4.9

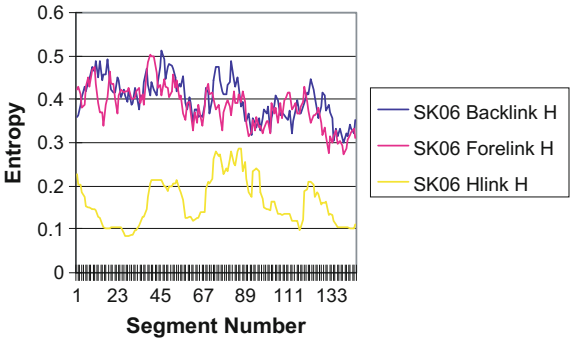

Fig. 6.14 Entropy variation in design session SK06 with total score of 4.9

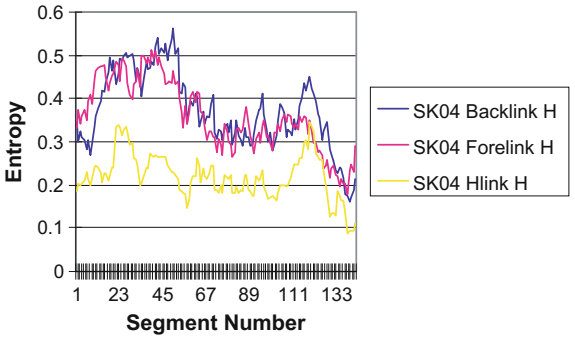

Fig. 6.15 Quadratic fit of entropy variation in design session SK04

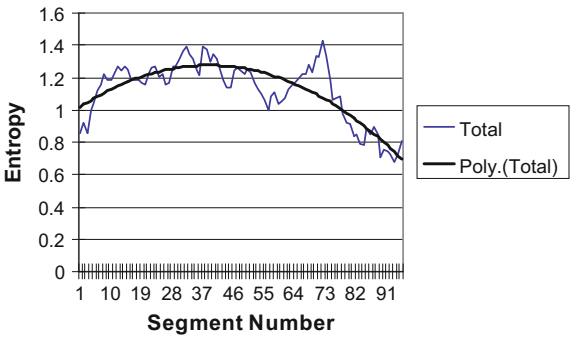

Fig. 6.16 Quadratic fit of entropy variation in design session BF06

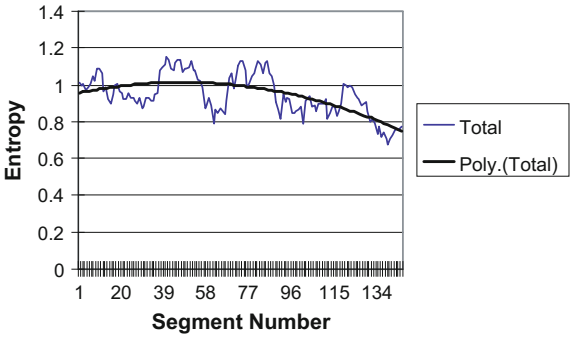

Fig. 6.17 Quadratic fit of entropy variation in design session SK06

All the high-scoring sessions have concave-shaped or negative curvature in the quadratic fit curves and all the low-scoring sessions have convex-shaped or positive curvature curves. The differential (slope or tangent) of the quadratic curve will be a straight line. The differential of the entropy curve denotes the rate of change in entropy. Figures 6.18, 6.19 and 6.20 show the differentials of the top three sessions and Figs. 6.21, 6.22 and 6.23 show the differentials of the bottom three sessions. They were plotted using the same scale.

The slopes of the differentials, i.e., rate of change in entropy, in the top three sessions are all positive. The change in entropy increases from negative to positive

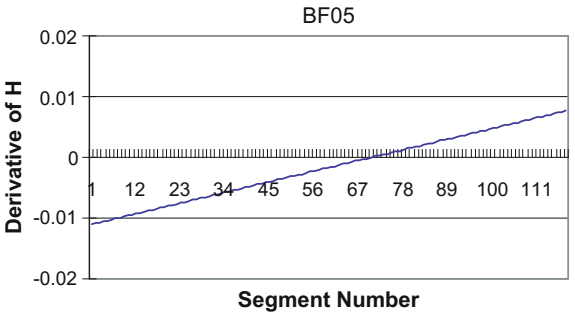

Fig. 6.18 Differential of the BF05 session

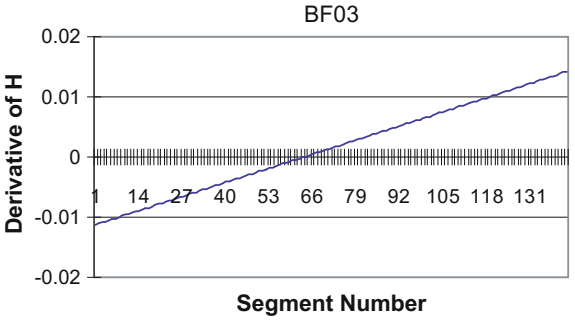

Fig. 6.19 Differential of the BF03 session

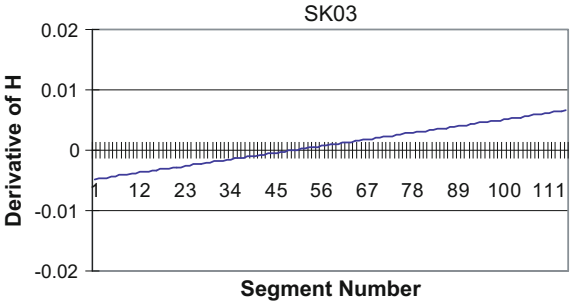

Fig. 6.20 Differential of the SK03 session

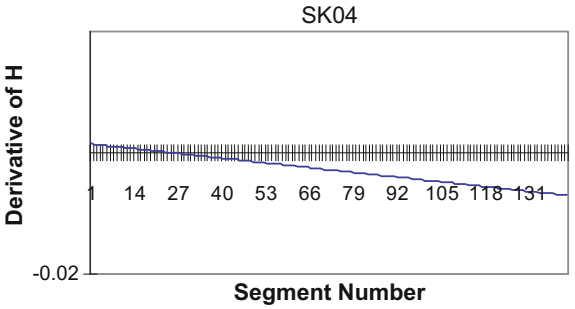

Fig. 6.21 Differential of the SK04 session

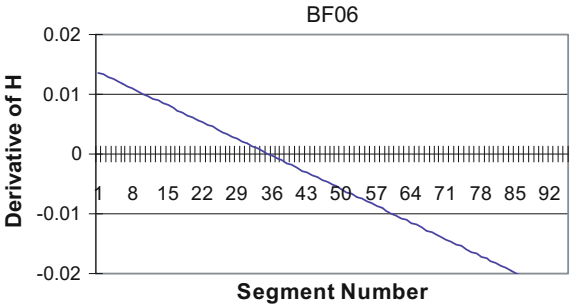

Fig. 6.22 Differential of the BF06 session

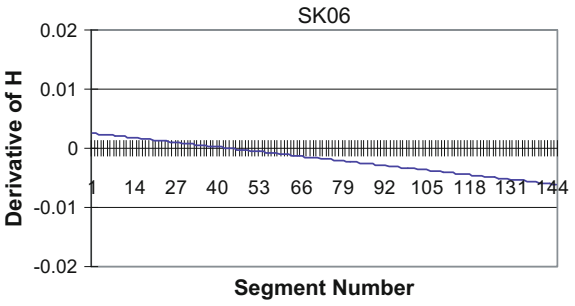

Fig. 6.23 Differential of the SK06 session

and becomes zero near the middle of the session. This is the opposite of what occurs in the low-scoring sessions, where the change in entropy decreases from positive to negative, and the slopes of the differentials are all negative.

For the high-scoring design outcome sessions the change in entropy increases from negative to positive while for the low scoring design sessions the change in entropy decreases from positive to negative within the 40 min session. A negative slop of the quadratic fit curves indicates the trend of getting less links while a positive slope suggests there is a move towards more links. In Figs. 6.18, 6.19 and 6.20, the high scoring sessions, the positive-sloped graphs cutting through zero suggest there was a change in the trend of linkages. In the first half (negative slop) of the session they started with more links and move toward less links and then changed (entropy equals zero) from fewer links to more links (positive slop). In comparison, in Figs. 6.21, 6.22 and 6.23, the low-scoring sessions, the trends were from moving towards more links and then moving towards less links.

6.7 Idea Contributions

Many researchers believe that there are prerequisites for the creation of useful ideas; among those experience and interactions play important roles. A good design idea not only fulfils the requirements but also has the quality of novelty and creativity. 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. If good design ideas exist, bad design ideas co-exist in relative terms. Bad ideas are those that are impractical, non-innovative, or unrealistic.

A move in a linkograph does not have any attributes nor does it have any value judgment assigned to it. It is assumed there are two fundamentally different types of moves, contributing and non-contributing moves, and that contributing moves build up good design ideas and non-contributing moves do not add values to good ideas. An integration of contributing moves will produce a good design outcome and an integration of non-contributing moves will not produce a good design outcome. If a design solution is based on poor assumptions or unrealistic expectations, the outcome would not be ranked highly.

SK04, the lowest-scoring session, was considered to be the most impractical design, as seen in Table 6.1. It has a relatively high linkograph entropy, listed in Tables 6.3 and 6.4. Could this designer have integrated her/his design based on some bad ideas or non-contributing moves? Reviewing the protocol, this designer made two major decisions very early without exploring other possibilities; (1) s/he decided to have a two-storey building, (2) s/he decided to centralise the building in the middle south side of the site. From the qualitative analysis, the designer of SK04 did not have a strong central idea for the design; 28 min were spent on revisiting the structural aspect of the design. This agrees with Bilda's (2006) description of this session. He identified eight episodes in this session; four of them

consisted of revising and relocating spaces. These did not seem to be contributing to good ideas besides reworking on the dimensions and locations. On the contrary, in the BF05 session, the highest-scoring one, the designer came up with many useful and practical ideas. For example, because the functions of the two studios are different, they will create different actions and sounds, which prompted the designer to separate the two studios; the analogy of the lighting behaviour of the Glasgow Art School studio space induced a window capturing the southern light; the idea of a courtyard together with the site imposed one long line of the studio spaces. Some other ideas that were not described in the qualitative analysis were: the garage roof that captures water, neighbours' and council's concerns about shadow, and a pavilion form.

If the FBS ontology were used to describe the SK04 session, one would expect that a lot of those segments would be coded as structure in the FBS ontology. Table 6.5 presents an example of those revisits of structure. The structure of the bedrooms were proposed in Segment 30 so it was coded as structure (S). In segment 66 the designer was not satisfy with the appearance (behaviour) of the facade so s/he started changing the location (Segment 67, coded as S) and proportion (Segment 68, coded as S) of the bedrooms. This kind of relocation and re-dimensioning did not introduce new variables. Out of the eight identified episodes, four of them contained this kind of structure revisiting.

Those ideas in the BF05 session would expect to be coded ranging from function and behaviour to structure. One would expect the types of reformulation to be richer in the BF05 session. An excerpt from BF05 with the FBS codes is presented in Table 6.6. The link from Segment 53 to Segment 52 is a type II reformulation.

Table 6.5 Examples of FBS coding for SK04

Segment	Transcript	Links	FBS code
30	The master bedroom is 20–25. I've forgotten the master bedroom. Okay, so that's another… I'll add that to my list. 20–25 m^2. Okay	29 28	S
66	Now I'm not quite happy with the amount of area I've used because it presents a very solid facade. I'd prefer to reduce the amount of bulk on the top floor at the front and shift some of this back	65 30 11	B
67	I could possibly also move some bedrooms around so that I have more of these facing the north and looking over the open space and not having two looking over the southern boundary. So I can see from what I have now if I take those two rooms, they could	66 30	S
68	If I reshape those proportions slightly, I'll draw them in approximately—6 m deep. Then I'll cross out the ones at the front and move them to the rear. That's bedrooms 3 and 4, I'll keep the same numbers	64 65 66 67	S

Table 6.6 Examples of FBS coding for BF05

Segment	Transcript	Links	FBS code
49	And that would also work for the art studio because it is on the facing east. Facing to the park. So it gets the morning sunlight, because you don't want to be in the cold	12 21 11 48	B
50	dance studio and then just getting westerly sun without the need really to be controlled so it don't get too hot	21	B
51	Ok, so that could work, your loo could go there so it would be a linear thing up there, feed off to, that could work. I am not quite sure about the size of the spaces but	43 46 42	S
52	I think it would be like an H plan and then you come into the centre, you would spread either way. Whether the circulation is becoming too much on the house. Maybe you don't do that. Maybe you have…	32 31 25	S
53	maybe you don't have a roof… or you just have an open connection or walkway. That could be quite nice. So your living spaces then connect onto that. So from your kitchen you could see right through	17 37 52 47 48	B
54	And then do you… you make the site, you don't have a specific garden, you have a big park. I get a sense that she is a painter, they are not real gardeners, but they may have…	25 31	F

From the analysis of the "H" shaped plan and the amount of circulation space prompt the designer to have the expected behaviour of open connection. This open connection was a new behaviour variable.

6.8 Conclusions

In the design sessions presented in this chapter, the design outcomes had certain relationships with the entropy of their linkograph. All the blindfolded (BF) sessions had a higher or equal score for the design outcome compared to their corresponding sketch (SK) sessions. This was reflected by the entropy of the linkographs: five out of six of the BF sessions had higher entropy than the corresponding SK sessions. However, higher entropy did not correlate with better design outcomes. All the high scoring-sessions had higher entropic measures toward the end of the design sessions as they become more integrated approaching the end. This was approximated by a quadratic fit with a negative curvature of entropy curves. The differentials of these quadratic curves yielded straight lines. The three highest-scoring sessions had a positive slope, while all the poor-scoring sessions had a negative slope. The decrease in entropy at the beginning of the good sessions was caused by fewer connections between moves, which could indicate diversification of ideas. The increase in entropy at the end of a session meant a better integration of moves,

which might indicate a consolidation of ideas. Does this mean that good designs need to diversify before consolidation? Is the change in entropy an indicator or a predictive tool for good design? With these limited cases, a firm conclusion cannot be reached. However, there are some indications in this case study that there is a correlation between the inter-segments entropy variation and the design processes and/or its outcome; the trend of entropy variation may reveal the outcome of the design. More experiments are needed to verify this claim. There was some evidence that suggested the design outcome could be related to the entropy of the linkograph. Also, FBS ontological coding is expected to help in identifying good design sessions, and this will be discussed in the next chapter.