Chapter 4
Ontologically-Based Studies of Design Protocols

This chapter presents the results of using an ontological approach to segment and code the protocol before constructing a linkograph. Design processes are then derived from the links. Four cases are being presented. The first case was a brainstorming session that involved a multi-disciplinary design team. In this case, the percentage of processes derived from the FBS coding scheme is compared with those derived from the situated FBS coding scheme. In the second case two architects collaborated in two different environments; one a face-to-face session and the other using a 3D virtual-world environment; the analyses of the two sessions are performed by using the situated FBS ontology. The third case uses statistical inferences to explore the effects of education on design. In case four, designing is viewed as a special class of problem solving; the FBS design issues is being mapped onto problem and solution spaces. This forms the basis of using the metacognitive design style of students to compare designerly behaviour in different domains.

4.1 Case One: A Brainstorming Session

The data for this case was an in situ design meeting distributed to researchers involved in the Design Thinking Research Symposium 7. The idea behind using a common set of protocol data was to find a more rigorous way to do empirical research into design (Cross 2007b). There were four sessions, two architectural and two engineering. One particular engineering session was selected because of its content. Since the architectural sessions contained mainly presentation and communication with clients, they contained comparatively fewer design activities. Both engineering sessions concerned brainstorming of a thermal printing pen, the first session was selected because it involved generating novel ideas related to the structure of an object. The other session focussed more on usage and control.

J.W.T. Kan and J.S. Gero, *Quantitative Methods for Studying Design Protocols*, DOI 10.1007/978-94-024-0984-0_4

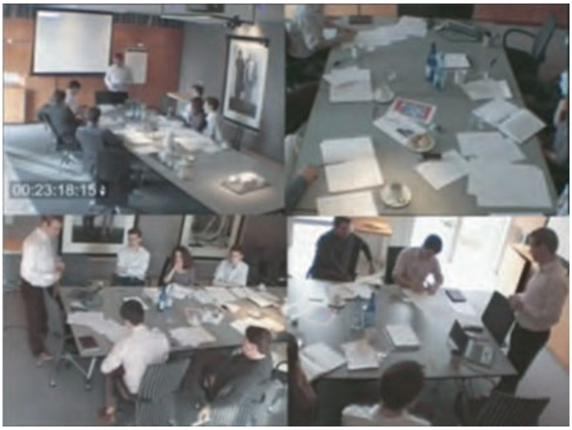


Fig. 4.1 Four camera digital recording of the brain storming session

The aim of this brainstorming session was to obtain ideas for a prototype of the thermal printing pen. This involved solving specific problems such as keeping the print head levelled with an optimum angle and protection of the print head. Seven cross-disciplinary participants were involved, with one acting as the moderator. The whole session lasted for 1 h and 37 min. Figure 4.1 shows a frame from the recording.

4.1.1 *Qualitative Analysis*

This protocol can be divided into two episodes; the first one concerned the problem of keeping the print head in contact with and at the optimum angle to the media, despite wobbly arm moment. The second episode dealt with protecting the print head from abusive use and overheating. In the first episode, participants were asked to generate ideas from available products that follow a contour. Several products were mentioned, such as a sledge, snowboard, wind surfboard, shaver, snow-mobile, train and slicer. Other concepts such as wheels, spirit level and laser leveller were also discussed. Loosely related to those analogies, a few proposed shapes, such as a mouse-type pen, were proposed. Besides product behaviour, user behaviour was also considered. Figure 4.2 shows some of the sketches the

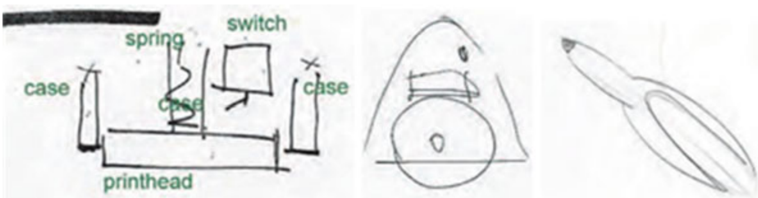


Fig. 4.2 Sketches from the brainstorming session

participants used in this session. On the left is a sketch of the structure they proposed near the end of the first episode; in the middle is a drawing of a toy a member suggested from which to borrow ideas; and on the right is one of the proposed forms of the thermal printing pen.

4.1.2 Segments and Coding

The verbal transcription of the protocol was segmented strictly according to the FBS ontology—each segment contains only one FBS code that represents the design issue in that segment. Segmenting and coding were undertaken simultaneously by discerning whether an action or utterance expresses the FBS aspect of designing. If an utterance contains more than one FBS issue it will be further divided. In the first round, the protocol was coded with the original FBS classes. Two additional codes were used: requirement (R) and others (O) to represent issues related to requirements and any other non-design related issues. The addition of the R code does not require any addition to the FBS ontology as R is expressible in terms of F, B or S. In Gero's (1990) FBS computational model, designing was assumed to start with function. Later in the Gero and Kannengiesser's (2004) situated FBS framework (a cognitive model), designing was viewed to start with requirements. The R code is used because in protocol studies the designing activities usually start with requirements instead of function. Table 4.1 shows some examples from the protocol for each code and Fig. 4.4 contains an extract of the coded protocol used to show the linkograph.

The first episode was coded twice by the first author with a 10-day separation and then self-arbitrated using the Delphi method proposed by Gero and McNeill (1998). The agreement between the codes is 86 %. Within the 52 min in this

Table 4.1 Example of coding

Issues	Protocol
Requirements (R)	"quite important is it's about the thermal-incli-inclis () pen" "design a-a prototype"
Function (F)	"that's the standard plain thermal paper err and then it can draw"
Expected behaviour (Be)	"either atoms or line types" "we can print thermo reactive dyes onto media substrates"
Behaviour (Bs)	"it'll be about 50 % more expensive" "if you lift an optical mouse slightly off the page you'll see the pattern it creates"
Structure (S)	"a sledge or a snowboar- a skis or snowboard" "show the relative size of the pen if you've got an example"
Design description (D)	Figure 4.2
Others (O)	"yeah, we'll come to that in a minute"

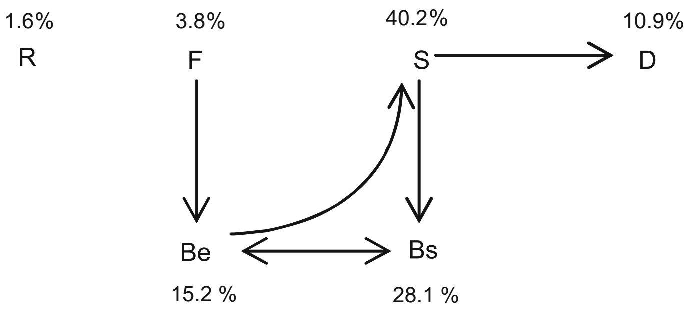


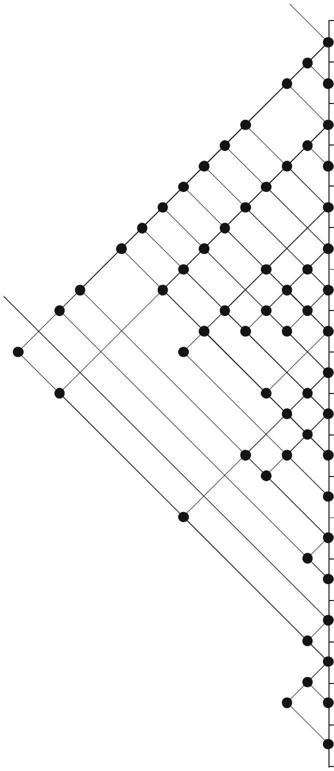
Fig. 4.3 Percentages of each code in relation the FBS framework

episode there were 475 segments. The average segment length is about 6.5 s. Of the segments, 448 segments have FBS issues; those segments without FBS issues (27) consist mostly of jokes or communications that are not related to the design process or the resulting artefact. Figure 4.3 shows the percentages in each of the FBS categories in relation to the processes of the FBS ontology. The highest percentages are in the structure and behaviour classes. In this protocol these high percentages were due to the frequent use of analogies with other products and situations.

4.1.3 Linking the Segments

In the first run of constructing the links, the connections between the segments were discerned independently of the code. After 4 months, the links were re-examined in conjunction with the codes. This was to increase the reliability in linking the segments. Figure 4.4 presents an extract of the coded protocol together with its linkograph. In the table part of Fig. 4.4 column one is the segment number, column two is the code and column three is the transcribed protocol.

In this extract two participants were involved, the moderator (A) and a mechanical engineer (J). The focus of the discussion was "other products or situations where a product needs to follow a contour". J suggested an object (structure) —"sledge" (segment 38)—and continued to explain the behaviour of the sledge, i.e., how it maintains contact or level on the snow (segment 40 and 48). The sledge was compared with a set of skis (segment 43) in terms of the structure (segment 44) and behaviour (segments 45, 47 and 48). The coding of segment 50 can be argued; it was coded as expected behaviour (Be) as we interpreted J was borrowing the behaviour of the analogised objects and targeting those to be the expected behaviour of the designed object. Finally, the structure of stabilisers (segment 53) was suggested. Segment 39 was linked to segment 38 because the "write sledge" action was a response to the initiation and suggestion of the "sledge" in segment 38.



38	S	J: I ended up with the + hold on +sledge
39	D	A: the sledge excellent so what did that generate then? (write: sledge)
40	Bs	J: the sledge manages to keep level by having quite a wide base
41	D	A: (write: wide base)
42	Bs	J: a main force in the middle
43	S	J: unlike the set of skis
44	S	J: where quite narrow and
45	Bs	J: you go up on an edge when you're turning
46	S	J: the sledge is er quite broad
47	Bs	J: and then you have the weight right in the middle
48	Bs	so they manage to keep both runners on the snow
49	D	A: (write: force in middle)
50	Be	J: a sledge or a snowboar- a skis or snowboard
51	S	A: some guiders almost down the side of this
52	Be	J: the easiest way to keep the pen at a right angle would be
53	S	J: to have a set of stabilisers on it based on the idea of a sledge
54	S	A: stabilisers +++like a bicycle yeah that's a good
55	D	A: (write: stabiliser)

Fig. 4.4 Rotated linkograph in relation to the protocols

J started explaining in segment 40 why a sledge was a proposed candidate for solution so segments 38 and 40 were linked. By examining the relationship of a segment with those preceding segments a linkograph was constructed. Figure 4.5 shows a larger part of the linkograph of this session that includes the above extract. Other clusters were also labelled. These clusters can be distinguished by visual inspection of link density or by statistical clustering.

There are 2110 links connecting the 448 segments, so on average each segment has 4.7 links. However, some segments have many more links than others. Table 4.2 compares the distribution of the codes of the segments with the occurrences of codes in the links. It shows the percentages of segments and links with the FBS code. Compared to the coded segments, it can be observed that the codes in the links have a decrease in the documentation, a moderate decrease in behaviour derived from structure and a slight decrease in function. The requirement has increased, and there is an increase in expected behaviour and structure as well. This implies that the expected requirements, behaviour and structure segments in this session are more influential because the designers took more notice of those linked segments.

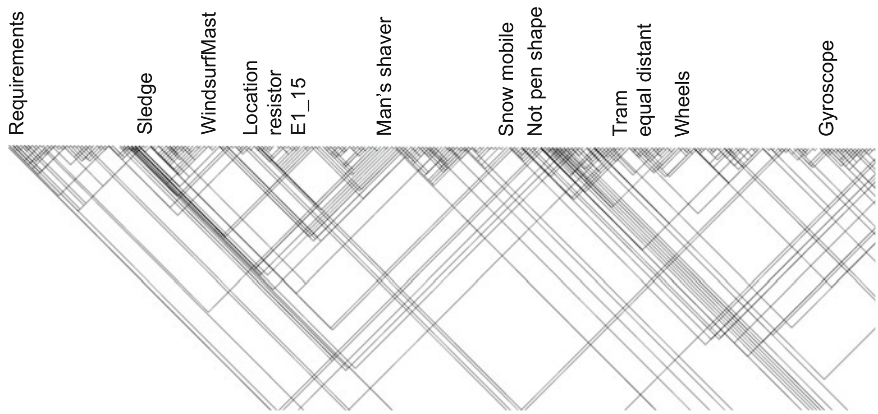


Fig. 4.5 Part of the linkograph of the segmented protocol

Table 4.2 The distribution of codes in segments and links

Code	Segment		Link	
	Count	Percentage	Count	Percentage
R	7	1.6	36	1.7
F	17	3.8	56	2.6
Bs	126	28.1	504	23.8
Be	69	15.4	396	18.7
S	180	40.2	936	44.3
D	49	10.9	187	8.8
Total	448	100.0	2110	100.0

4.1.4 Deriving Semantic FBS Processes from Coded Segments and Links

In the following analysis, the symbol "⇝" is used to denote the link between the nth and the (n + i)th segments to avoid confusion with the transformation symbol "→" (see Chap. 3, Sect. 3.1.2). For example, consider the first segment linking to the two subsequence segments in Fig. 4.4, S ⇝ D was used to represent the link between segments 38 and 39. S ⇝ Bs was used to represent the link between segments 38 and 40, Fig. 4.6 illustrates this example. S ⇝ D can be seen as the documentation process (transformation from structure to design description, S → D) and the S ⇝ Bs as the analysis process (transformation structure to behaviour, S → Bs) according to the ontology. There may be cases where the links might not correspond to the eight FBS processes.

The 2110 links can be viewed as design processes since each link has an FBS code at each end. Thus, looking back from one coded segment to the segment at the other end of the link we have a transformation from one coded issue to another, i.e.,

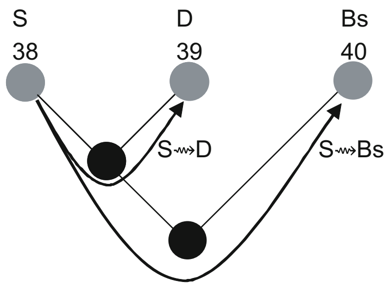


Fig. 4.6 Deriving transformation processes from linkograph

a design process, and the linkograph then becomes a network of transformation processes. There are seven categories of codes, including O, so there will be 49 types of possible transformations. However, according to the FBS ontology, many of those processes have no direct meaning in design. For example, a process that involves O will have no design significance. Table 4.3 shows the FBS-related processes derived from the links of the segments with FBS issues. There are 30 types of FBS processes recorded; those FBS processes in the framework are represented in Table 4.4.

In this episode, the reformulations were mostly of structure and behaviour. The sledge example in Fig. 4.4 contains the reformulation of structure (S ⇝ S), from the structure of a sledge to the structure of a set of stabilizers like those in a bicycle, segment 38–53 and 53–54.

Table 4.3 Percentages of all the processes derived from codes and links

R		F		Bs		Be		S		D	
R ⇝ Bs	1.3	F ⇝ Bs	0.2	Bs ⇝ Bs	8.4	Be ⇝ Bs	4.9	S ⇝ Bs	12.2	D ⇝ Bs	0.5
R ⇝ Be	0.2	F ⇝ Be	1.1	Bs ⇝ Be	5.0	Be ⇝ Be	6.9	S ⇝ Be	3.3	D ⇝ Be	0.9
R ⇝ F	0.1	F ⇝ F	1.4	Bs ⇝ D	0.9	Be ⇝ D	1.8	S ⇝ D	5.3	D ⇝ D	1.4
R ⇝ R	0.3	F ⇝ R	0.1	Bs ⇝ F	0.5	Be ⇝ F	0.1	S ⇝ F	0.1	D ⇝ S	5.4
R ⇝ S	1.0	F ⇝ S	0.1	Bs ⇝ S	2.7	Be ⇝ S	6.9	S ⇝ R	0.1		
								S ⇝ S	26.7		

Table 4.4 Percentages of the eight FBS processes

Processes		Occurrence	Percentage
Formulation	R → F, F → Be	14	1.4
Synthesis	Be → S	68	6.9
Analysis	S → Bs	120	12.2
Documentation	S → D	52	5.3
Evaluation	Be ↔ Bs	48(Be ⇝ Bs), 49(Bs ⇝ Be) 97	9.9
Reformulation I	S → S	262	26.7
Reformulation II	S → Be	32	3.3
Reformulation III	S → F	1	0.1
	Total	646	65.9

Other examples of structure reformulations were: making analogies with other products, for example a wind surfboard mast and man's shaver and considering the thermal pen in the shape of other things instead of a pen. Examples of behaviour reformulations were: using a universal joint to keep the angle; using springs to keep it level; and suggesting the locations of resistors, which prompted the responses regarding the cost.

The reformulation of function was rare, which reflects the nature of this session —mechanical brainstorming for ideas to keep the thermal pen in contact with the media at the correct angle. Some of the function aspects are deliberately not dealt with. For example the suggestion of "could we, sorry, could we actually see what they're doing? I mean, are they drawing pictures or making invitations or Christmas cards or—" was given the response of "erm we're going to try to deal with that a fair bit on Monday".

The FBS ontology covers two-thirds of the processes derived from the links of the coded segments. The segments that are not design related can be coded as "Other" with an "O". These segments can be deleted from the segmented/coded protocol when carrying out only design-related analyses. If we delete segments coded as "O" the coverage increases to three-quarters. Some of the most frequent processes not counted were: Bs ⇝ Bs (8.4 %), Be ⇝ Be (6.9 %), D ⇝ S (5.4 %), S ⇝ Be (3.3 %), Bs ⇝ S (2.7 %), and Be ⇝ D (1.8 %).

Reviewing the protocol, in the case of Bs ⇝ S, it can be noted that the large scale of the granularity fails to pick up the Be in the Bs ⇝ S processes. If the granularity of segmentation were finer, there should be an expected behaviour before the structure code. Using the example in Fig. 4.4, segment 40: "the sledge manages to keep level by having quite a wide base" was coded as Bs because it analyzes an existing product to get the "keep level" behaviour. This segment was linked to segment 53: "the easiest way to keep the pen at a right angle would be to have a set of stabilizers on it based on the idea of a sledge" which was coded as structure because it proposed a structure, "a set of stabilizers". The idea of sledge, the behaviour of "keep level", was translated to expected behaviour of "at a right angle" which leads to the structure of "a set of stabilizers".

The F ⇝ F and Be ⇝ Be can be viewed as reflections of function and behaviour in many cases. An example of Be ⇝ Be happened when they discussed that the shape of the designed object does not need to resemble a pen. The moderator suggested that "…something else that gets pulled behind it for example" and an engineer's response, "…what they'll do is move the lump around" were linked and both segments were coded as expected behaviour (Be).

The D ⇝ S is the interpretation of depicted structure. The Bs ⇝ Bs usually is a result of further analysis, for example in Fig. 4.4 link between segments 40 and 42 and link between segments 42 and 48 were further analysis of the action and reaction of the force (weight). Sometimes the Be ⇝ D transformation was the depiction of behaviour but the FBS ontology does not distinguish depiction of behaviour from depiction of structure unless we use subclasses as shown in Fig. 3.20. Using the above example again, "…what they'll do is move the lump around" was linked to the following segment where the moderator was writing down "(move lump)", which is a depiction of behaviour. These transformations are meaningful processes resulting from the interactions among members and artifacts. The situated FBS ontology covers all these processes.

4.1.5 Syntactic Design Processes: Markov Analysis

There are 475 segments and 448 of them contain situated FBS codes. If they are considered as first-order Markov processes, there will be 447 state changes. Table 4.5 lists the occurrence of all those state changes. There is no record of any Fe occurrence, so it was taken out for ease of matrix manipulation. Using the data in Table 4.5, the transition matrix, Eq. 4.1, can be obtained. The highest probability of transition was from B^e to Be^i. This indicates that an event of depiction of behaviour has a near 50 % chance to be followed by an event of expected behavior as shown in the results in Eq. 4.1.

$$P_{dtrs} = \begin{pmatrix} & R & F^i & Fe^i & B^i & Be^i & B^e & S^i & Se^i & S^e \\ R & 0.43 & 0.00 & 0.14 & 0.29 & 0.14 & 0.00 & 0.00 & 0.00 & 0.00 \\ F^i & 0.00 & 0.13 & 0.25 & 0.25 & 0.00 & 0.00 & 0.38 & 0.00 & 0.00 \\ Fe^i & 0.00 & 0.44 & 0.00 & 0.00 & 0.44 & 0.00 & 0.00 & 0.11 & 0.00 \\ B^i & 0.00 & 0.02 & 0.03 & 0.38 & 0.19 & 0.02 & 0.25 & 0.08 & 0.03 \\ Be^i & 0.01 & 0.00 & 0.01 & 0.19 & 0.28 & 0.12 & 0.04 & 0.35 & 0.00 \\ B^e & 0.00 & 0.00 & 0.08 & 0.15 & 0.46 & 0.00 & 0.00 & 0.31 & 0.00 \\ S^i & 0.02 & 0.00 & 0.00 & 0.39 & 0.03 & 0.00 & 0.32 & 0.17 & 0.07 \\ Se^i & 0.00 & 0.00 & 0.00 & 0.17 & 0.12 & 0.04 & 0.19 & 0.20 & 0.28 \\ S^e & 0.00 & 0.00 & 0.00 & 0.20 & 0.06 & 0.00 & 0.40 & 0.29 & 0.06 \end{pmatrix} \quad (4.1)$$

Table 4.5 Occurrence of the sequence of situated FBS codes

State	Next state								
	R	F^i	Fe^i	B^i	Be^i	B^e	S^i	Se^i	S^e
R	3	0	1	2	1	0	0	0	0
F^i	0	1	2	2	0	0	3	0	0
Fe^i	0	4	0	0	4	0	0	1	0
B^i	0	3	4	47	24	2	31	10	4
Be^i	1	0	1	13	19	8	3	24	0
B^e	0	0	1	2	6	0	0	4	0
S^i	2	0	0	38	3	0	31	17	7
Se^i	0	0	0	14	10	3	16	17	23
S^e	0	0	0	7	2	0	14	10	2

Probability Vector

Putting P_{dtrs} into Eq. 3.2 and solving the equations, the probability vector is:

$$a_{dtrs} = \begin{pmatrix} R & F^I & Fe^I & B^I & Be^I & B^e & S^I & Se^I & S^e \\ 0.01 & 0.02 & 0.02 & 0.28 & 0.15 & 0.03 & 0.22 & 0.19 & 0.08 \end{pmatrix} \quad (4.2)$$

This distribution is similar to the distribution of codes in segments. With a large number of segments, Eq. 4.2 predicts that 28 % of the codes are B^i, 22 % of the codes are S^i, 19 % of the codes are Se^i, 15 % of the codes are Be^i, 8 % of the codes are S^e, 3 % of the codes are B^e, 2 % of the codes are F^i, 2 % of the codes are Fe^i and 1 % of the code is R.

First Passage Times

Using P_{dtrs} and α_{dtrs} together with Eqs. 3.4 and 3.5, the mean first passage times can be obtained:

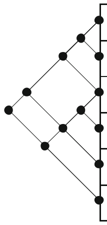
$$M_{dtrs} = \begin{pmatrix} & R & F^i & Fe^i & B^i & Be^i & B^e & S^i & Se^i & S^e \\ R & 84.7 & 66.1 & 43.7 & 4.3 & 6.9 & 35.8 & 7.6 & 7.5 & 15.4 \\ F^i & 146.8 & 56.8 & 41.7 & 4.1 & 8.8 & 36.8 & 4.5 & 7.3 & 14.6 \\ Fe^i & 147.2 & 42.0 & 51.3 & 5.4 & 5.8 & 34.9 & 6.5 & 6.2 & 14.3 \\ B^i & 146.9 & 70.9 & 55.5 & 3.6 & 7.5 & 35.1 & 5.2 & 6.3 & 13.5 \\ Be^i & 145.3 & 73.7 & 56.8 & 4.7 & 6.5 & 30.8 & 6.6 & 4.3 & 13.0 \\ B^e & 147.2 & 72.1 & 53.7 & 4.9 & 5.2 & 34.1 & 6.9 & 4.4 & 13.2 \\ S^i & 143.9 & 73.6 & 57.7 & 3.3 & 9.0 & 36.5 & 4.6 & 6.0 & 12.6 \\ Se^i & 147.1 & 74.5 & 58.5 & 4.4 & 8.4 & 34.9 & 5.1 & 5.3 & 9.8 \\ S^e & 146.6 & 74.4 & 58.5 & 4.1 & 9.0 & 36.5 & 4.1 & 5.2 & 12.3 \end{pmatrix} \quad (4.3)$$

The shortest mean passage time is from S^i to B^i and the longest one is from Fe^i to R. This matrix agrees with the general hypothesis that it is faster to move from any behaviour states to a structure state than from any function states to a structure state.

These statistically-derived models of designing provide a detailed level of understanding based on empirical evidence rather than relying only on a qualitative assessment. As a consequence it becomes possible to compare quantitative results from disparate studies (Gero and Jiang 2016).

4.1.6 Deriving Situated FBS Processes

The segments were recoded with the situated FBS scheme; readers can refer to Chap. 3, Sect. 3.4.3, for the ten categories. For ease of comparison, the segments have not been refined, so the total numbers of segments and total number of links



38	S^i	J: I ended up with the + hold on +sledge
39	S^e	A: the sledge excellent (write: sledge) so what did that generate then?
40	B^i	J: the sledge manages to keep level by having quite a wide base
41	S^e	A: (write: wide base)
42	B^i	J: a main force in the middle
43	S^i	J: unlike the set of skis

Fig. 4.7 Rotated linkograph showing the situated FBS coding of the protocol

will be the same. The protocol was coded twice by the first author and then self-arbitrated.

Figure 4.7 illustrates the recoding from segments 38–43. Segment 38 was coded as S^i because J was showing a picture of a sledge and was about to draw an analogy with the structure of the sledge. The main activity in segment 39 was writing down the word "sledge". It was treated as the documentation of structure as the word "sledge" denoted the object, so it was coded as S^e. Segment 40 was coded as Bi because it interpreted behaviour ("keep level") of the sledge. Segment 41 was coded as Se since it was a depiction that concerns the structural aspect ("wide base") of the object. Segment 42, similar to segment 40, involves the interpretation of behavioural aspect ("a main force in the middle") of the object, so the Bi code was assigned. Segment 43 concerns another object "skis" which was coded as S^i.

Table 4.6 shows the distributions of codes in the segments and links and their percentages. There is no documentation of function. It shows that expected behaviour, expected structure and interpreted structure are more influential than they appear in the segments, while the interpreted function and behaviour, the expected

Table 4.6 Comparing the distribution of codes in segments and links

	Segments		Links	
	Count	%	Count	%
R	7	1.6	36	1.7
F^i	8	1.8	18	0.8
F^e	0	0.0	0	0.0
Fe^i	9	2.0	38	1.8
B^i	125	27.9	493	23.3
B^e	13	2.9	42	2.0
Be^i	69	15.4	396	18.7
S^i	98	21.9	485	22.9
S^e	36	8.0	145	6.9
Se^i	83	18.5	462	21.8
Total	448	100.0	2126	100.0

Table 4.7 Percentages of FBS processes with situated FBS coding

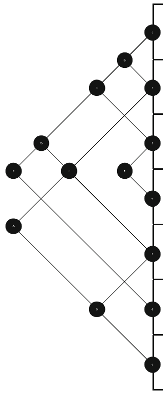
Process		%
Formulation	$R \rightsquigarrow B^i$, $R \rightsquigarrow F^i$, $R \rightsquigarrow S^i$, $Fe^i \rightsquigarrow Be^i$, $F^i \rightsquigarrow Be^i$	3.4
Synthesis	$Be^i \rightsquigarrow Se^i$, $B^i \rightsquigarrow Se^i$	7.5
Analysis	$S^i \rightsquigarrow B^i$, $S^e \rightsquigarrow B^i$, $Se^i \rightsquigarrow B^i$	13.4
Evaluation	$Be^i \rightsquigarrow B^i$	4.6
Documentation	$Be^i \rightsquigarrow B^e$, $B^i \rightsquigarrow B^e$, $Be^i \rightsquigarrow S^e$, $Se^i \rightsquigarrow S^e$, $S^i \rightsquigarrow S^e$	8.1
Reformulation I	$Se^i \rightsquigarrow Se^i$, $Se^i \rightsquigarrow S^i$, $S^i \rightsquigarrow Se^i$, $S^i \rightsquigarrow S^i$, $S^e \rightsquigarrow S^i$, $S^e \rightsquigarrow Se^i$	31.7
Reformulation II	$Be^i \rightsquigarrow Be^i$, $B^i \rightsquigarrow Be^i$, $B^i \rightsquigarrow B^i$, $B^e \rightsquigarrow Be^i$ $B^e \rightsquigarrow B^i$	21.6
Reformulation III	$B^i \rightsquigarrow F^i$, $Fe^i \rightsquigarrow Fe^i$, $Fe^i \rightsquigarrow F^i$, $F^i \rightsquigarrow Fe^i$	1.5
Total		91.9

function, and the depiction of behaviour are of less importance than they appear in the segments.

Using the situated FBS variables as the codes, 50 types of derived FBS-related processes were recorded. Those meaningful processes were then aggregated into the basic eight design processes. For clarity and ease of analysis, the interpretation and reflection categories of processes were separated from the formulation and reformulation processes, so that there is no overlapping of processes in any of the categories. This gave a 92 % coverage of the derived processes, as seen in Table 4.7. The middle column of the table represents the derived processes that were being aggregated. The percentages of all the derived processes are documented in Appendix E, Table E.1.

Compared to the original FBS, there is an increase in the capture of the reformulations. The increase is most noticeable for Reformulation II (behaviour) for this protocol.

The remaining 8 % contain processes like $B^i \rightsquigarrow S^e$ and $B^i \rightsquigarrow S^i$. Figure 4.7 contains both examples, the derived process from segment 40 to 41 is an example of $B^i \rightsquigarrow S^e$. The processes from links between segments 42 $\rightsquigarrow$ 43 and 40 $\rightsquigarrow$ 43 are examples of $B^i \rightsquigarrow S^i$. In the first round of coding, segment 40 "the sledge manages to keep level by having quite a wide base" was coded as B^i; in the second round it was coded as S^i. The final arbitrated code was B^i. It should contain two parts—the behaviour part of "keep level" and the structural part "wide base". Segment 43 "unlike the set of skis" was also one of those codes about which there was disagreement (B^i and S^i). The final code was S^i but by carefully examining the context the analogy of "unlike" was both structure and behaviour; the structure analogy was "wide base" against "narrow", the behaviour analogy was "force in the middle" versus on one leg. Figure 4.8 illustrates a proposed refinement of the segments from segment 40 to 43 together with the codes and linkograph. The first column in the table contains the segments with an alphabetic suffix added to those subdivided segments. The links were updated so that they corresponded to the processes of the ontology.



40a	S^i	J: the sledge by having quite a wide base
40b	B^i	J: manages to keep level
41a	Se^i	A:[interpret and expecting the "wide base" structure of a sledge]
41b	S^e	A: (write: wide base)
42	B^i	J: a main force in the middle
43a	S^i	J: unlike the set of skis [in terms of structure]
43b	B^i	J: unlike the set of skis [in terms of behaviour]

Fig. 4.8 Proposed finer grain of re-segmenting and recoding

The missing processes (8 %) were caused by the lack of experience in using this coding method; this includes choosing the correct granularity and making appropriate links. In this case some of the segments require a finer grain than was used. Further analysis and refinement is likely to resolve these "missing" processes as exemplified above.

4.1.7 Findings in Case One

The FBS ontology denotes fundamental processes of designing that are general enough to embrace almost all design situations. Unlike most coding schemes, supported by available protocol analysis software that allows overlapping of codes, the ontological approach requires precise discernment of one code per segment. This clear distinction converts the protocol into unambiguous segments; it quantifies the amount of effort spent in relation to function, behaviour or structure. The links not only provide a structural view of the processes but also locate the dominant codes and the frequency of each design transformation process. The nested representation of links, the linkograph, together with the FBS-coded segments provide an opportunity to look into the design protocol not in a linear manner, but as a network of processes.

The use of the FBS ontology has been able to capture the design semantics of this protocol. Of particular interest is that formulation/reformulation is the largest activity in terms of events and that the vast majority of reformulation is concerned with behaviour and structure. This maps well to our qualitative understanding of this session—generating ideas by analogy. The FBS-based coding scheme accounts for 92 % of all designing activities in this protocol. Later protocol studies brought the percentage of design activities accounted for closer to 100 % (Jiang 2012).

4.2 Case Two: Face-to-Face Versus Computer-Mediated

In this case, data were obtained from the CRC for Construction Innovation project (Kan and Gero 2008b). In that project in vitro studies were conducted with five pairs of designers. One pair was selected for this study. The most creative face-to-face session, judged by the design outcome, was selected for analysis. In the experiments each pair was asked to collaborate in three different settings: face-to-face, Internet Group Board and a 3D virtual world. Group Board is a shared drawing-board environment, in which designers could communicate via the Internet in remote locations. The version used was a commercial version. The 3D virtual world is an extension of Active World and includes video contact, a shared whiteboard and an object viewer/insert of building objects. The design tasks were to generate conceptual designs; each session lasted for 30 min and began with briefs of similar complexity. The same site was used in all the sessions. In the face-to-face session the designers were asked to design a contemporary art gallery. The brief for the Internet Group Board sessions was an architectural library for the university; and the brief for the 3D virtual world was a dance studio. Prior to the computer-mediated experiments, there were training sessions to acquaint the participants with the operations of the different environments. For the analysis, all the sessions were video-recorded. Figure 4.9 shows a frame of the digital recording of the 3D-world session; two of the channels recorded their screens. Their full resolution screens were also captured at three frames per second, illustrated at top left and bottom right in the figure.

The Group Board session was not studied, because Maher et al. (2006) showed in their analysis that in the Group Board session, designers behaved either similarly to the face-to-face session or in the mid-ground between the face-to-face and 3D virtual-world session.

Fig. 4.9 Digital recording of the 3D-world session

4.2.1 Qualitative Analysis

A1 and A2 are used to represent the two participants in this section. In all the sessions A1 seemed to take the leadership role and made decisions; he drew most of the sketches in the face-to-face session and organised most of the activities in the 3D virtual-world session.

Face-to-Face Session

The face-to-face session can be divided into four stages or episodes, based on the design activities. In the first episode the two designers dealt with the brief and site (about 3.5 min); in the second episode they analysed, planned and developed concepts in the plan (Fig. 4.10, about 9 min); in the third episode they developed the 3D form in elevation (Fig. 4.11, about 9 min); and in the final episode they worked on the layout in the plan until the end (Fig. 4.12, 8.5 min), but they did not finish it within the 30 min allocated for the session.

They started by analysing the site. Both of them knew the site, although A2 got the orientation wrong. In the second episode, after analysing the site A1 suggested the location of the main approach and started drawing. A2 suggested the location of the service entrance. Issues such as an icon to capture attention, internal and external relationships, and permeability were discussed. Also, the location for the main exhibition, the back of the house, and a merchandising area were suggested (Fig. 4.10). Afterwards A2, using another sheet (Fig. 4.11), suggested the elevations and the idea of a “ribbon”, but A1 provided a counter proposal—the “hole in the middle” idea—by drawing an isometric view (Fig. 4.11). In the third episode, they combined the two ideas and further developed it in the plan (bottom left of Fig. 4.11). Eventually A1 drew the 3D form (right of Fig. 4.11). In the last episode, they tried to resolve the dimensions and constraints of the design, which involved calculations (Fig. 4.12).

Fig. 4.10 First two sheets of plans in the first and second episode

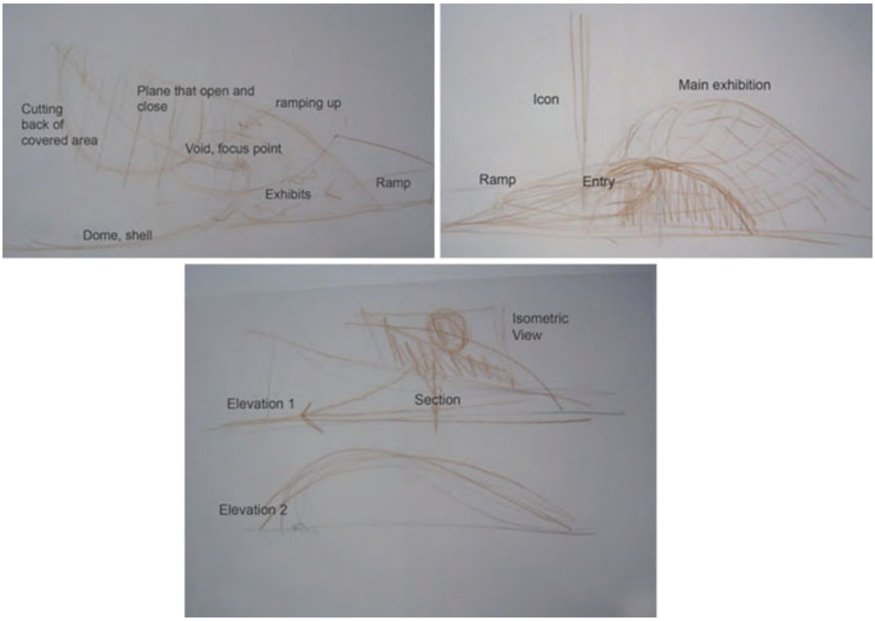
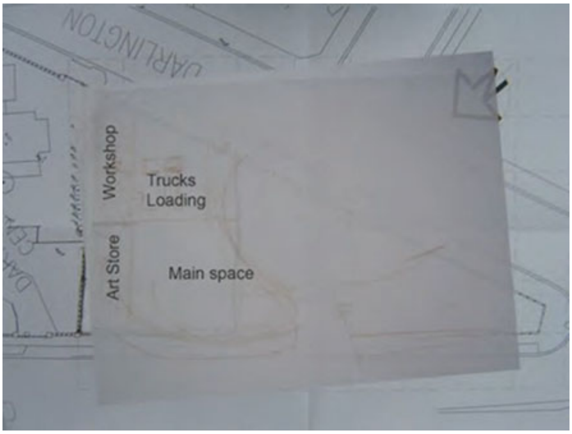


Fig. 4.11 Plans, section and elevation in the third episode

Fig. 4.12 Plan in the last episode



3D-World Session

In the 3D-world session, the stages were not as well defined as in the face-to- face session; they spent less than 2 min with the brief before exploring and making objects. This session can be characterised as “designing through making”. Sometimes they subdivided the tasks and worked individually. They were given pre-defined elements—space, slab, wall, column and beam—in various sizes. They decided to start with the biggest space element to represent the “largest” spaces, the

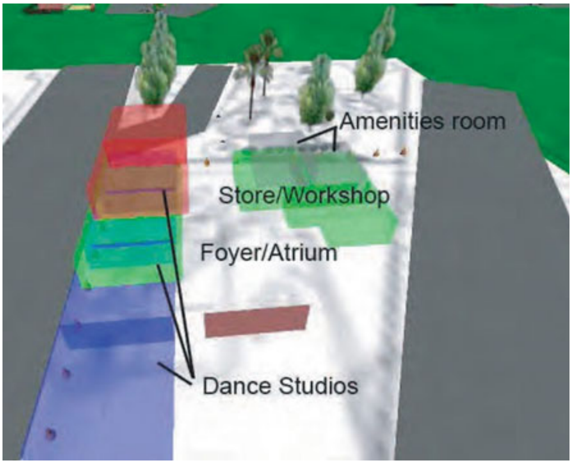


Fig. 4.13 Final design of the 3D-world session

four studios. At around 12 min, they discovered they could not have all the studios on one level because of the site coverage constraint. A1 decided to stack them and create an atrium to join them together. They tried to further develop this concept to accommodate the requirements (Fig. 4.13). A1 repeatedly went to pick up those space objects of relevant size for A2 to arrange on the site.

They did not finish the design and left out elements such as connecting bridges and some functional spaces. Besides designing, time was spent on design support activities, such as discussing what elements were available and organising what to do. Also, time was spent on the technical aspects of learning how to do things, such as changing the colour of the blocks, how to "fly", and how get out when "trapped inside" those blocks.

Comparing the Two Sessions

This section qualitatively compares the two sessions. In terms of the design outcome, as seen in Figs. 4.11 and 4.13, the styles of the designs were very different. The design of the face-to-face session was free-form and organic, while the design of the 3D-world session was orthogonal.

In terms of the process, in the face-to-face session the design process was closely coupled, while in the 3D virtual-world session the process was loosely coupled. In the 3D-world session the designers tended to work more individually. Working individually led to the issue of the sense of presence.

The designers made used of the avatar in the 3D virtual-world to detect the other party; also they used the web cam. Issues about the sense of presence often appeared in the protocol in the 3D-world session, such as: "…you're not looking my way anyway", "the camera is not directed at you", and "I can't see you though…, I don't know where you are…". Also, they lost the ability to gesture. The design actions occurred through interaction with keyboard and mouse. In the face-to-face session they relied on gesturing to communicate; they gestured paths, shapes and circulations. They also used gestures to signal turn-taking with the drawing.

The length of the verbal protocol in the face-to-face session was not only longer but also more concentrated on designing. There was more non-design activity in the 3D-world protocol. For example, communication regarding the software: "how do change the colour", communication related to the location of each other: "where are you?", communication regarding the ownership of objects "now you've taken it away", and other social communication: "it's superman". The amount of time during which they remained silent was also longer in the 3D-world session. Even in design-related communication, they were more concerned with achieving tasks; this can be explained by the limitation of the software, for example: "I pick it up…", "we bring it across…", and "… because it is filled by blocks".

In terms of idea development, the designers developed more design ideas in the face-to-face setting than in the 3D virtual-world setting. There were a number of concepts besides organising the space, such as: "make it a journey of discovery", "the ribbon idea", "hole in the middle", "ramping … this whole platform" and "dropping into the centre". These ideas co-evolved in the problem and solution space and it is difficult to pinpoint what triggered these ideas. What was observed matched what Finke et al. (1992) described as many processes collectively setting the stage for creative insight and discovery. In the 3D-world session, the main idea was the "atrium". Although there were fewer ideas, the designers still switched between the problem and solution space.

4.2.2 *Ontological Coding of Both Sessions*

The design protocols were segmented according to the situated FBS ontology, as described in Sect. 3.4.3 of Chap. 3.

Table 4.8 is an extract of the coded protocol of the face-to-face session. The segmentation is based on the FBS ontology. Segment 13 was a response triggered by attending to the requirement of "size" in the brief. The architect was expecting to obtain structural data by pulling data from the brief, therefore it was coded as "S^i". Segments 14 and 16 were read from the brief so they were coded as "R". Segments 15 and 17 represented the interpretation of the behavioural and structural requirements, so they were coded as "B^i" and "S^i" respectively. Segment 18 recalled a famous museum by Frank Gehry. From the context it seemed to refer to the structure, expecting the gallery to look like "the Guggenheim". This gave a new meaning to the understanding of the design. In segment 15 the architect interpreted the gallery as "typical" when referring to the "permanent and temporary" collection

Table 4.8 An extract of the coded protocol of the face-to-face session

Segments	Protocol	Code
13	Okay hang on, it's talking about sizes here	S^i
14	So … (read brief) permanent and temporary	R
15	Typical	B^i
16	(read brief) Permanent collection is 200 and 50 m hanging space	R
17	50 m hanging space!	S^i
18	This is the Guggenheim	Se^i

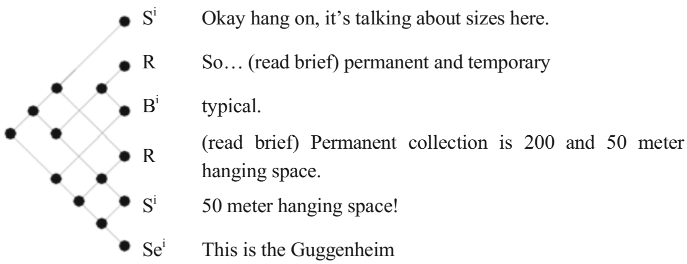


Fig. 4.14 Example of linkograph in relation to protocol

space; this interpretation was changed in the light of the current situation. Figure 4.14 shows the coded protocol together with the linkograph constructed by discerning how segments are related.

The coding of the first 11 min of both sessions are used here. There were 205 segments and 95 % of them contained FBS codes in the face-to-face session. There were 125 segments in the 3D-world sessions and 51 % of them contained FBS codes. The low percentage in the 3D-world was a result of learning how to do things, especially in the beginning, like "how to fly", "how to get out", and "how to change colour". Actions of the mouse and keyboard in the 3D-world session were not segmented, so no external world actions were coded. Regardless, there was a high percentage of structure, which corresponded to the "design by making".

There are 595 links in the face-to-face session and 92 links in the 3D-world session. Figures 4.15 and 4.16 compare the percentages of each code of the two sessions in the segments and in the links respectively. In the 3D session many actions and activities were not captured because no verbalisation occurred while the designers were using the keyboard. These actions include the manipulation of objects in the 3D-world.

The segments that are not design related can be coded as "Other" with an "O". These segments can be deleted from the when carrying out only design-related analyses.

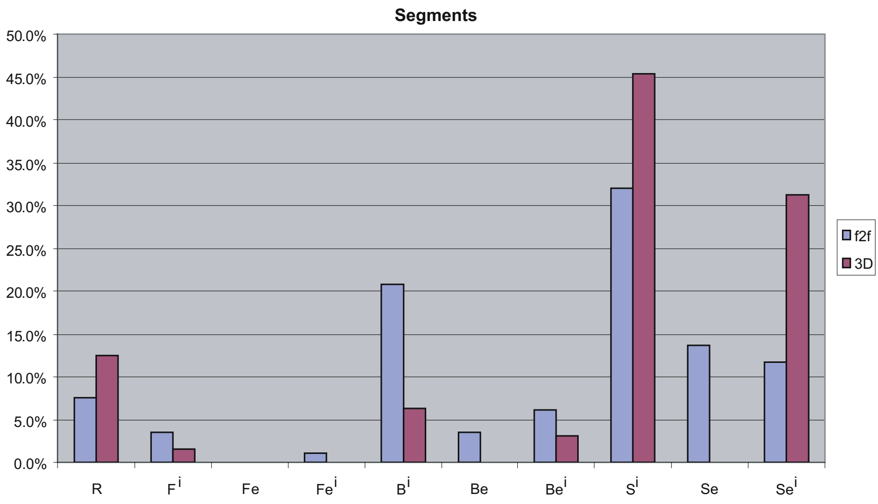


Fig. 4.15 The distributions of codes in the segments of the face-to-face and the 3D-world sessions

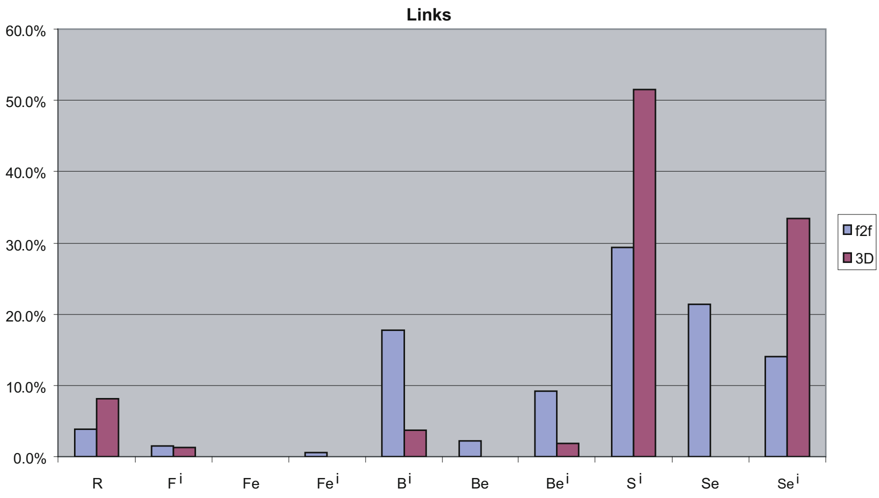


Fig. 4.16 The distributions of codes in the links of the face-to-face and the 3D-world sessions

4.2.3 The Eight FBS Processes of Both Sessions

Processes were derived from the links. If segments coded as O are included some of these processes are meaningless, because some segments do not have an FBS code. Using a similar method to that described in Case One, the derived processes were

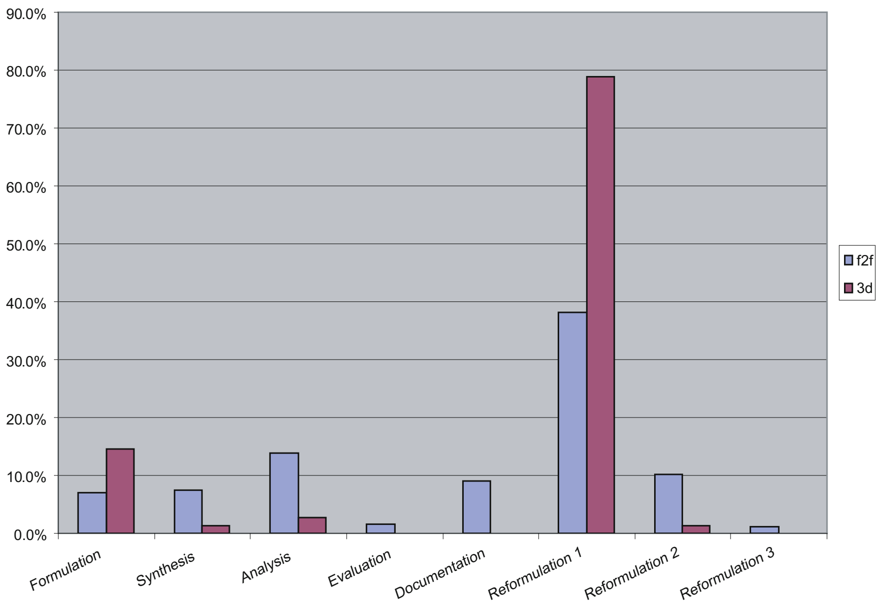


Fig. 4.17 The eight FBS processes of the face-to-face and the 3D-world sessions

grouped into the eight FBS categories. Figure 4.17 compares the percentages of the grouped processes. This shows and compares the distribution of processes but not the quantity of those processes. For example, the 79 % of the type one reformulation process in the 3D-world session has 60 processes but the 38 % in the face-to-face session has 225 processes.

In the face-to-face session, these eight processes add up to about 89 % of all the derived processes, while in the 3D-world they aggregate to about 99 %. Again, the missing processes, especially in the face-to-face session, were caused by the granularity of the segments. There is no documentation process in the 3D-world session, because no external world actions were coded. Also, there is no evaluation process; this is the result of coding only the first 11 min. In this short period, the designers hardly had anything to evaluate but had a considerable amount to formulate. The percentages of all the derived processes are documented in Appendix E, Tables E.2 and E.3.

All three types of reformulations were present in the face-to-face session, but no Reformulation 3 was found in the 3D-world session. Both sessions have a relatively high type one reformulation. The face-to-face session has higher analysis, synthesis and evaluation processes. These matched the qualitative understanding of the sessions. In the 3D-world session the predominant process was the reformulation of structure, the re-making of forms.

4.2.4 Markov Analysis

There are 197 segments containing situated FBS codes in the face-to-face session, so there will be 196 state changes. In the 3D-world session there are only 63 state changes. Tables 4.9 and 4.10 list the occurrences of all those state changes in the face-to-face and 3D-world respectively. From the tables, the transition matrices, P_{f2f} and P_{3d} (Eqs. 4.4 and 4.5), can be obtained. In the face-to-face session, the highest probability of transitions were from S^i to S^i (0.52). The next two were Fe^i to Be^i and S^i, both were 0.5. This happened because the occurrence of Fe^i was rare, only happening twice. From Be^i to S^e also had the transition probability of 0.5. The transition probability from B^e to B^i was also high, 0.43. The highest transition probability of the 3D-world session was from B^i to R.

$$P_{f2f} = \begin{pmatrix} & R & F^i & Fe^i & B^i & Be^i & B^e & S^i & Se^i & S^e \\ R & 0.20 & 0.20 & 0.00 & 0.13 & 0.00 & 0.07 & 0.40 & 0.00 & 0.00 \\ F^i & 0.29 & 0.14 & 0.14 & 0.29 & 0.14 & 0.00 & 0.00 & 0.00 & 0.00 \\ Fe^i & 0.00 & 0.00 & 0.00 & 0.00 & 0.50 & 0.00 & 0.50 & 0.00 & 0.00 \\ B^i & 0.10 & 0.02 & 0.02 & 0.34 & 0.17 & 0.05 & 0.22 & 0.02 & 0.05 \\ Be^i & 0.08 & 0.00 & 0.00 & 0.00 & 0.00 & 0.17 & 0.00 & 0.25 & 0.50 \\ B^e & 0.14 & 0.00 & 0.00 & 0.43 & 0.00 & 0.00 & 0.29 & 0.14 & 0.00 \\ S^i & 0.05 & 0.02 & 0.00 & 0.13 & 0.00 & 0.02 & 0.52 & 0.13 & 0.14 \\ Se^i & 0.00 & 0.00 & 0.00 & 0.14 & 0.09 & 0.05 & 0.14 & 0.23 & 0.36 \\ S^e & 0.04 & 0.00 & 0.00 & 0.33 & 0.04 & 0.00 & 0.33 & 0.19 & 0.07 \end{pmatrix} \quad (4.4)$$

Table 4.9 Occurrence of the sequence of situated FBS codes in the face-to-face session

State	Next State								
	R	F^i	Fe^i	B^i	Be^i	B^e	S^i	Se^i	S^e
R	3	3	0	2	0	1	6	0	0
F^i	2	1	1	2	1	0	0	0	0
Fe^i	0	0	0	0	1	0	1	0	0
B^i	4	1	1	14	7	2	9	1	2
Be^i	1	0	0	0	0	2	0	3	6
B^e	1	0	0	3	0	0	2	1	0
S^i	3	1	0	8	0	1	33	8	9
Se^i	0	0	0	3	2	1	3	5	8
S^e	1	0	0	9	1	0	9	5	2

Table 4.10 Occurrence of the sequence of situated FBS codes in the 3D-world session

State	Next state					
	R	F^i	B^i	Be^i	B^e	S^i
R	1	0	3	0	4	0
F^i	1	0	0	0	0	0
B^i	3	0	0	0	1	0
Be^i	0	0	0	1	0	1
B^e	1	1	0	0	18	8
S^i	1	0	1	1	6	11

$$P_{3d} = \begin{pmatrix} & R & F^i & B^i & Be^i & S^i & Se^i \\ R & 0.13 & 0.00 & 0.38 & 0.00 & 0.50 & 0.00 \\ F^i & 1.00 & 0.00 & 0.00 & 0.00 & 0.00 & 0.00 \\ B^i & 0.75 & 0.00 & 0.00 & 0.00 & 0.25 & 0.00 \\ Be^i & 0.00 & 0.00 & 0.00 & 0.50 & 0.00 & 0.50 \\ S^i & 0.04 & 0.04 & 0.00 & 0.00 & 0.64 & 0.29 \\ Se^i & 0.05 & 0.00 & 0.05 & 0.05 & 0.30 & 0.55 \end{pmatrix} \tag{4.5}$$

Probability Vector

Putting P_{f2f} (Eq. 4.4) into Eq. 3.2 and solving the equations, the probability vector for the face-to-face session is:

$$a_{f2f} = \begin{pmatrix} R & F^i & Fe^i & B^i & Be^i & B^e & S^i & Se^i & S^e \\ 0.07 & 0.03 & 0.01 & 0.21 & 0.06 & 0.04 & 0.32 & 0.12 & 0.14 \end{pmatrix} \tag{4.6}$$

This distribution is similar to the distribution of codes in segments. With a large number of FBS segments, 32 % of the codes are predicted to be S^i, 21 % of the codes are predicted to be B^i, 14 % of the codes are predicted to be S^e, 12 % of the codes are predicted to be Se^i, 10 % of the codes are predicted to be the combination of Be^i and B^e, 7 % of the codes are predicted to be R and 4 % of the codes are predicted to be the combination of F^i and Fe^i.

Similarly, putting P_{3d} (Eq. 4.5) into Eq. 3.2 and solving the equations, the probability vector for the 3D-world session is:

$$a_{3d} = \begin{pmatrix} R & F^i & B^i & Be^i & S^i & Se^i \\ 0.10 & 0.02 & 0.06 & 0.03 & 0.46 & 0.33 \end{pmatrix} \tag{4.7}$$

This distribution is also not far from the distribution of codes in segments. The Markov probability predicts fewer R and B^i codes. The analysis predicts S^i and S^e will occupy nearly 80 % of the codes with a large number of segments. Comparing this to α_{f2f} (Eq. 4.6), the 3D-world session is predicted to have more structure codes.

First Passage Times

Using P_{f2f} and α_{f2f} together with Eqs. 3.4 and 3.5 the mean first passage times for the face-to-face session can be obtained:

$$M_{f2f} = \begin{pmatrix} & R & F^i & Fe^i & B^i & Be^i & B^e & S^i & Se^i & S^e \\ R & 13.5 & 32.5 & 102.1 & 5.9 & 16.4 & 26.6 & 3.7 & 11.7 & 8.7 \\ F^i & 12.2 & 34.2 & 87.2 & 5.3 & 12.6 & 27.3 & 5.4 & 11.7 & 8.3 \\ Fe^i & 18.0 & 43.4 & 107.5 & 7.0 & 9.4 & 27.1 & 3.6 & 10.0 & 6.5 \\ B^i & 15.8 & 40.8 & 102.6 & 4.8 & 13.3 & 26.2 & 4.6 & 10.8 & 7.5 \\ Be^i & 16.7 & 42.7 & 106.7 & 6.0 & 16.5 & 24.0 & 5.2 & 8.3 & 4.3 \\ B^e & 15.3 & 41.3 & 105.2 & 4.3 & 16.0 & 27.9 & 4.2 & 10.1 & 8.1 \\ S^i & 17.2 & 42.0 & 106.3 & 5.9 & 16.9 & 28.3 & 3.1 & 9.7 & 6.8 \\ Se^i & 18.1 & 43.4 & 106.8 & 5.6 & 14.9 & 26.9 & 4.9 & 8.4 & 4.8 \\ S^e & 17.3 & 42.6 & 106.0 & 4.8 & 15.6 & 28.1 & 4.0 & 9.3 & 7.1 \end{pmatrix} \tag{4.8}$$

In general it takes longer to move from F to S^e than from B to S^e. It is unexpected that the first passage time from Be^i to S^e is shorter than from Se^i to S^e. Further investigation is required to explain this.

Similarly, using P_{3d} and α_{3d} together with Eqs. 3.4 and 3.5 the mean first passage times for the 3D-world session are:

$$M_{3d} = \begin{pmatrix} & R & F^i & B^i & Be^i & S^i & Se^i \\ R & 9.6 & 59.6 & 14.8 & 65.1 & 2.3 & 6.5 \\ F^i & 1.0 & 60.6 & 15.8 & 66.1 & 3.3 & 7.5 \\ B^i & 4.5 & 60.0 & 18.0 & 65.5 & 2.7 & 6.9 \\ Be^i & 15.7 & 62.7 & 24.5 & 30.3 & 5.4 & 2.0 \\ S^i & 13.9 & 57.3 & 23.8 & 62.8 & 2.2 & 4.2 \\ Se^i & 13.7 & 60.7 & 22.5 & 58.6 & 3.4 & 3.0 \end{pmatrix} \tag{4.9}$$

4.2.5 Findings and Discussion for Case Two

Maher et al. (2006) concluded that the characteristics of the design process are quite different in sketching and 3D virtual environments. The preliminary results confirm that by showing the difference in the distribution of processes. Also, the amount of reformulation processes were much higher in the face-to-face session, which corresponded to the designers having developed more design ideas in the face-to-face setting than in the 3D virtual-world settings.

In order to perform a more rigorous comparison between the face-to-face and the 3D-world session, the protocol of the 3D-world session will need re-segmenting to include actions such as copying objects, changing object's colour, and navigating/moving in the 3D world. It will be helpful to have the logs of the designers' interactions for consultation. Also, the length of the protocol studied in the 3D world session was too short to cover a greater variety of different types of processes.

The study of the interactions among the FBS classes and processes in a set of design sessions rather than a single session can help to deepen the understanding of designing in a 3D-world situations, which can then inform the development of tools that aid designing in this environment.

4.3 Case Three: Statistical Exploration of the Effects of Education on Design Cognition

In this case we present an exploration by Williams et al. (2011) in which they employed hypothesis testing using FBS coding to study the effects of education on design cognition. Along with Student's *t* test (as explained in Chap. 3) other statistical techniques such as the Shapiro–Wilk W test was used. The principle of setting up the null hypothesis and getting the *p* value was the same. In this case, the authors report on progress of a longitudinal study on the impact of design education on students' design thinking and practice. Data gathered from two experimental sessions (conducted before and after the students' introductory design course) are analysed to identify changes in their design cognition regarding the FBS-coded design issues and the syntactic design processes.

4.3.1 Participants and the Experimental Setup

The participants of this case were second-year Mechanical Engineering students enrolled in a design course—Engineering Design and Economics—that aimed to expose them to engineering design and design methodologies at an early stage in their professional development. The 3-credit design course is centred on active-learning opportunities that allow students to apply their learning in engineering design. Classroom meetings are typically devoted to hands-on team based activities, which range from product dissections (internal combustion engines, air compressors, electric drills, disposable cameras, etc.) to various speculative design scenarios. These activities provide an opportunity for the instructor to perform individual mentoring and instruction. In addition to these in-class activities, student design teams work together out-of-class on a semester project where they design a novel consumer product.

The data collected of this study represents the beginning of the students' formal design education and experience. At this stage, the students' design education is

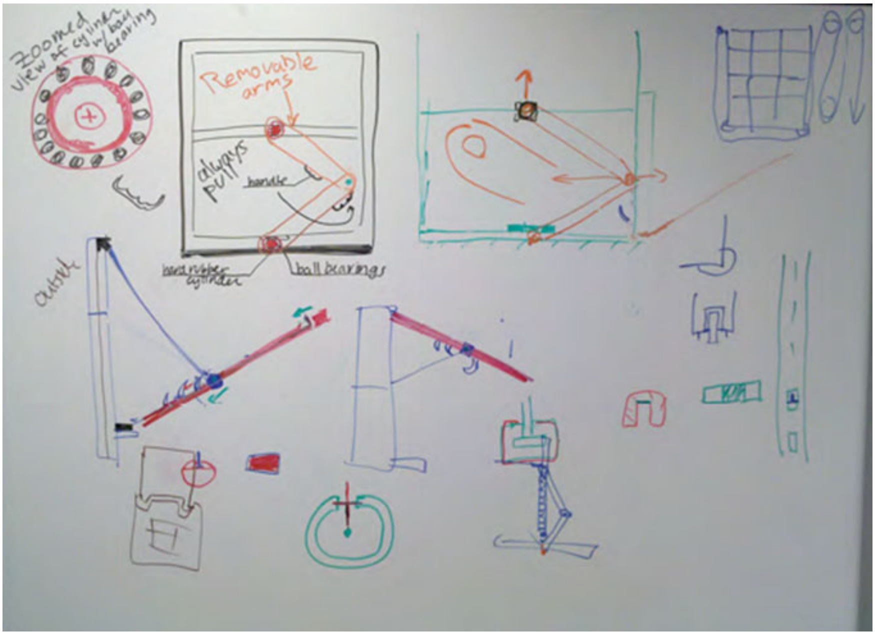


Fig. 4.18 Participant white-board sketch examples

limited to a 4-week "Introduction to Engineering Design" module in their first-year introductory engineering course. In order to make sure students are novices, those with significant design experience (either professionally or through prior academic experience), were screened through a preliminary interview and were not selected as participants.

Participants were asked to attend two out-of-class experiments: one at the beginning of the fall semester of their sophomore year; the other in the middle of the spring semester of the same academic year. In these experiments, pairs of students worked together at a white board to solve a speculative design task. A total of 28 students (16 in fall 2009 and 12 in spring 2010) participated the design session. Figure 4.18 shows examples of typical sketches produced during the design session.

Participants were paired up and given 45 min to come up with a design solution that meets the requirements in the provided brief. The entire design sessions were audio and video recorded for analysis. Two digital camcorders were used, one recording the whiteboard and the other recording the participants. Each participant had individual remote microphones to ensure the recording quality of their conversation. These raw data were segmented according to the FBS design issues.

4.3.2 Results and Findings of Case Three

Design Issues

The distributions of design issues before and after the introductory design course are illustrated in Fig. 4.19, with descriptive statistics reported in Table 4.11.

In both data sets it is observed that students spent the majority of their cognitive effort discussing design structure (37–40 %), followed by behaviour from structure (30–32 %). These two design issues accounted for two-thirds of their cognitive effort. Much less cognitive effort was spent on the design issues of description (9–15 %), expected behaviour (6–11 %), function (2–7 %), and requirement (2–3 %). The variations between before and after being exposed to the design course have been identified for each design issue. The percentages of their cognitive effort related to design function and design description have increased approximately 5 and 6 % respectively, whereas the percentages for all the other design issues have decreased. JMP 9.0, a statistical software package, was utilized to identify any statistical differences in the percentages of cognitive effort related to individual design issues before and after the course. Statistically significant differences were

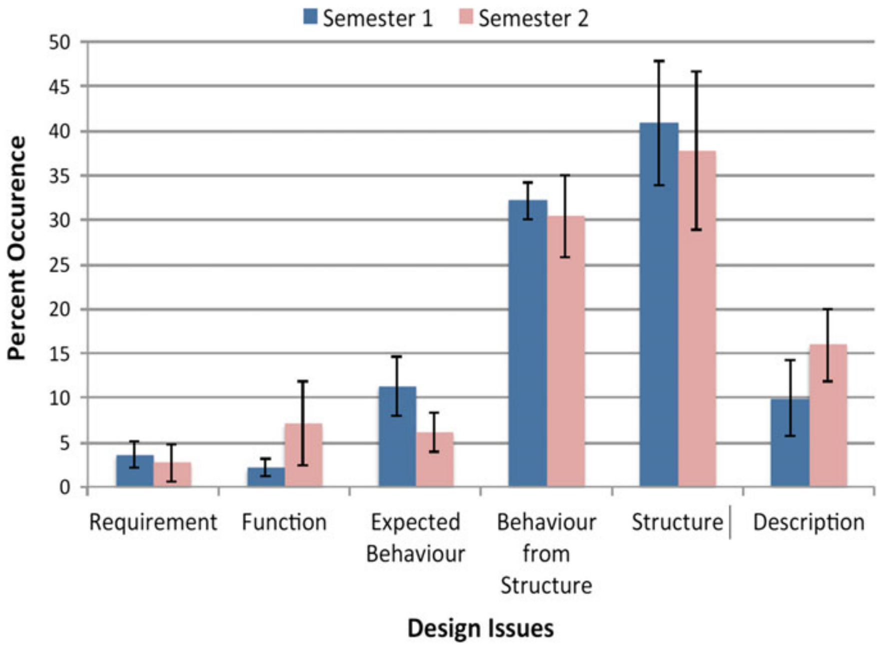


Fig. 4.19 Percent occurrences of design issues before (Semester 1) and after (Semester 2) exposure to design teaching

Table 4.11 Means and standard deviations of design issues before (Semester 1) and after (Semester 2) exposure to design teaching

Issue distribution	Semester 1 (n = 8) mean (SD)	Semester 2 (n = 6) mean (SD)
Requirement	3.62 (1.46)	2.70 (2.10)
Function	2.16 (1.07)	7.10 (4.67)
Expected behavior	11.31 (3.32)	6.13 (2.22)
Behavior from structure	32.13 (2.12)	30.37 (4.58)
Structure	40.88 (7.01)	37.75 (8.83)
Description	9.91 (4.22)	15.93 (4.10)

assumed at a significance level (α) of 0.05. The normality assumption was tested for each design issue using the Shapiro–Wilk W test. Only the percentage of cognitive effort on the design issue of function rejects the null hypothesis, which states that the data are from the normal distribution. Therefore, the Wilcoxon rank sum test, a non-parametric statistical analysis, was used for the design issue of function, whereas two-sample t tests were used for the rest. The results for these statistical analyses are reported in Table 4.12.

The statistical analyses indicate that there are significant differences regarding the percentages of cognitive effort in the three design issues of function, expected behaviour, and description between the two semesters. In semester 2, students were more engaged in discussions related to the design function, which is the teleology of their design solution. Specifically, many students attempted to jointly optimize their design for two criteria: design for the users (patients) and design for the customer (rehabilitation institute). Students intended to solve the initial problems with their design, yet also aimed to add or modify the functionalities of their design based on criteria such as safety, security, or possibilities to failure.

The percentage of cognitive effort on the design issue of expected behaviour significantly decreased from Semester 1 to Semester 2, after taking a design course. It is possible that this cognitive change could be caused by the design course's 3-week focus on problem formulation and functional decomposition. In these portions of the course students are taught to scope a design problem by identifying customer needs, transforming them into target specifications, completing a needs-metrics matrix and formulating function structures.

Table 4.12 Design issues comparisons between Semester 1 and Semester 2 statistical analysis results

Design issue	t(z) statistics	p value
Requirement	−0.925	0.137
Function	2.904	0.003**
Expected behaviour	−3.495	0.004**
Behaviour from structure	−0.879	0.409
Structure	−0.717	0.490
Description	2.685	0.021*

*$p < 0.05$; **$p < 0.01$

The percentage of cognitive effort on the design issue of description significantly increased after taking a design course. This increase could be due to the introductory design course as well—a major learning goal of the course is effective oral and written communication of design outcomes. As a result, students might be more confident in explaining their designs.

No significant differences in the percentages of cognitive effort on the design issues of requirement, behaviour from structure, and structure between the two semesters were identified.

Syntactic Design Processes

The syntactic design process distribution was computed to identify differences between before and after an introductory design course. The occurrences of syntactic processes for the two semesters are illustrated in Fig. 4.20, with descriptive statistics reported in Table 4.13.

The majority of students' cognitive effort was expended on reformulation I (29–33 %) and analysis (28 %), which accounted for almost two-thirds of their cognitive effort. Much less cognitive effort was spent on the design processes of documentation (10–16 %), evaluation (7–10 %), synthesis (6–8 %), reformulation II (4–6 %), reformulation III (1–4 %), and formulation (1 %). Some differences

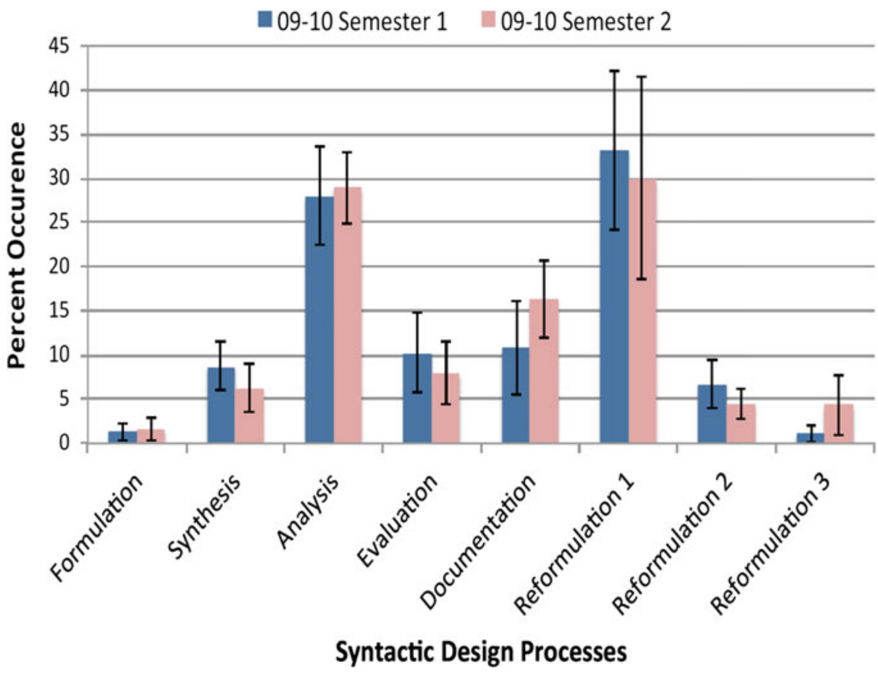


Fig. 4.20 Percent occurrences of syntactic design processes before (Semester 1) and after (Semester 2) exposure to design teaching

Table 4.13 Means and standard deviations of design issues before (Semester 1) and after (Semester 2) exposure to design teaching

Syntactic process distribution	Semester 1 (n = 8) mean (SD)	Semester 2 (n = 6) mean (SD)
Formulation	1.32 (1.01)	1.65 (1.30)
Synthesis	8.70 (2.66)	6.28 (2.70)
Analysis	28.00 (5.55)	28.95 (4.08)
Evaluation	10.23 (4.44)	7.96 (3.57)
Documentation	10.77 (5.31)	16.30 (4.43)
Reformulation I	33.18 (9.00)	29.98 (11.42)
Reformulation II	6.72 (2.70)	4.45 (1.69)
Reformulation III	1.06 (0.92)	4.38 (3.43)

were identified between the two semesters for each design process. A large increase in the percentages of students' cognitive effort for documentation (+6 %) and reformulation III (+3 %) were identified, whereas a slight increase was identified for formulation (0.33 %) and analysis (0.95 %). The cognitive effort for design processes of synthesis, evaluation, and reformulation II have decreased approximately 2 %, whereas, reformulation I decreased 3 %.

Two-sample t-tests were used to identify significant statistical differences in the percentages of cognitive effort related to individual design processes before and after the course, as shown in Table 4.14. As the percentage of cognitive effort on the design process of reformulation III did not follow the normal distribution, the Wilcoxon rank sum test was used.

The results indicate that there is a significant difference of the percentage of cognitive effort on the design process of reformulation III. The design process of reformulation III represents changes in the design function when the actual behavior is evaluated to be unsatisfactory (Gero and Kannengiesser 2004). The result reveals that the students were more engaged in the design process of modifying design

Table 4.14 Syntactic design processes comparisons between Semester 1 and Semester 2 statistical analysis results

Syntactic process	t(z) statistics	p value
Formulation	0.506	0.624
Synthesis	−1.666	0.124
Analysis	0.368	0.718
Evaluation	−1.059	0.155
Documentation	−0.567	0.584
Reformulation I	−0.567	0.584
Reformulation II	−1.931	0.077
Reformulation III	2.070	0.038*

$^*p < 0.05$

issues of function based on their analysis of design structures. As explained in Sect. 4.1, the significant increase of discussions related to the design function in semester 2 provides some evidence of such result.

A smaller pattern of difference between the two semesters was identified for the design process of reformulation II. The design process of reformulation II addresses changes in the design behaviour when the actual behaviour of a design structure is evaluated to be unsatisfactory (Gero and Kannengiesser 2004). This indicates that the students displayed a tendency of decreased engagement in the design process of modifying design issues of expected behaviour based on their analysis of design structures. The result is supported by the significant decrease of discussions of expected behaviour reported in Sect. 4.3.1.

The results highlight that there were significant differences in students' design cognition between before and after an introductory design course. Particularly, the design issues of function and description have significantly increased, while expected behaviour significantly decreased. The syntactic design process of reformulation III significantly decreased as well.

4.4 Case Four: Metacognition of Designing—Problem-Solution Index

Metacognition usually refers to cognition about one's own cognition (Flavell 1979). Dunlosky and Metcalfe (2009) give examples of using metacognition to improve our daily lives such as writing a note when it is essential to remember something. A large part of their model of metacognition concerns monitoring and controlling cognitive memory and processes. In the area of design cognition, it is often modelled as a search process across two notional design "spaces" of problem and solution. Problem (or Project) Based Learning has been used in many architectural school as a pedagogical approach for student to learn design, like the Department of Architecture, University of Newcastle, New South Wales, Australia, Technical University of Delft (TUDelft), Netherlands and the Department of Architecture and Civil Engineering, City University of Hong Kong. Problem-based learning is increasingly used in engineering and more recently in computer science education. We consider metacognition of designing, in a narrow sense, as the meta-level structure over the cognitive processes behind design problem and solution spaces; in other words how problem or solution focus is organized in the design cognitive process. Similar to case 4, we would like to explore if education in a particular domain will have any influence in the students' metacognition. In this section we use a study by Jiang et al. (2012) to illustrate the potential of using the FBS ontology for this kind of design research inquiry.

4.4.1 FBS Design Issues Mapping and Problem-Solution Index

In the FBS ontology, problem formulation mainly involves reasoning about requirement, function and expected behaviour, while reasoning about structure and behaviour from structure are related to artefacts as a solution to the formulated problem The ontologically-based design issues can then be categorized into problem-focused and solution-focused design issues as shown in Table 4.15.

The problem–solution (P–S) index is proposed as a ratio measurement, computing the ratio of the sum of the design issues concerned with the problem space to the sum of those related to the solution space, Eq. 4.10.

$$\text{P}-\text{S index} = \frac{\sum(\textit{Problem-related issues})}{\sum(\textit{Solution-related issues})} = \frac{\sum(R, F, Be)}{\sum(Bs, S)} \tag{4.10}$$

The P–S index value quantifies the relative focusing on problem or solution. When the P–S index equals one, it indicates that equal cognitive effort has been spent in the problem and solution spaces. We define a design session with a P–S index larger than 1 as one with a problem-focused metacognitive designing style, and a session with a P–S index value less than or equal to 1 as one with a solution-focused metacognitive design style.

4.4.2 The Experiment

24 final-year undergraduate design students participated in this study, 12 from Industrial Design (ID) and 12 from Mechanical Engineering (ME). Two participants, either from the same discipline or different ones, were paired to work collaboratively in two conceptual design tasks. The combination of design teams according to disciplines were: ID, ME and Mixed teams. The design tasks were used based on Keinonen's (2006) taxonomy of product development concepts and visionary concepts. The first task was to design a coffee maker (CM) for the existing market. It simulated a typical initial stage of a normal new product development (NPD) process. Designers were expected to consider practical factors

Table 4.15 Mapping FBS design issues onto problem and solution spaces

Problem/solution space	Design issue
Problem space = Problem-focused design issues	Requirement (R) Function (F) Expected behaviour (Be)
Solution space = Solution-focused design issues	Behaviour from structure (Bs) Structure (S)

related to a NPD project, e.g., market and user analysis, supporting technology and resources. The second task was to design a next-generation personal entertainment system (PES) for the year 2025. Task PES had a very limited amount of determined/unalterable factors. Designers were expected to use design concepts as a tangible means to explore future scenarios.

4.4.3 Results and Findings

The results present below suggest that industrial design student teams have a metacognitive design style that is more focused on the design problem than mechanical engineering student teams. This can be seen in the descriptive statistics where they had high frequency of function and expected behaviour issues; a higher value of P–S index; and a significantly higher P–S index value in the first half of the design sessions.

Descriptive Statistics

Each design session's occurrences of design issues were normalized by dividing them with the total number of design issues in that session. The normalized design issue distributions are shown in Table 4.16 and Fig. 4.21.

Table 4.16 Normalized distribution of design issues (%)

Groups	Design issues					
	Requirement (R)	Function (F)	Expected behavior (Be)	Behavior from structure (Bs)	Structure (S)	Description (D)
ID CM						
Mean	0.9	23.6	15.6	20.7	20.3	19.0
SD	0.4	2.8	4.2	3.8	1.7	6.7
ID PES						
Mean	1.5	28.0	23.1	15.7	13.2	18.7
SD	0.6	3.9	2.9	2.4	3.3	4.4
Mix CM						
Mean	0.9	17.9	12.7	27.4	21.5	19.6
SD	0.4	7.9	1.0	6.6	3.0	2.3
Mix PES						
Mean	1.5	17.3	14.4	27.2	18.0	21.6
SD	0.5	2.9	3.6	8.4	4.5	5.2
ME CM						
Mean	1.8	11.4	13.5	28.0	28.3	16.9
SD	0.4	6.0	3.7	3.2	8.2	5.4
ME PES						
Mean	1.1	12.1	15.6	31.2	19.8	20.1
SD	0.4	2.9	6.2	7.2	2.9	7.0

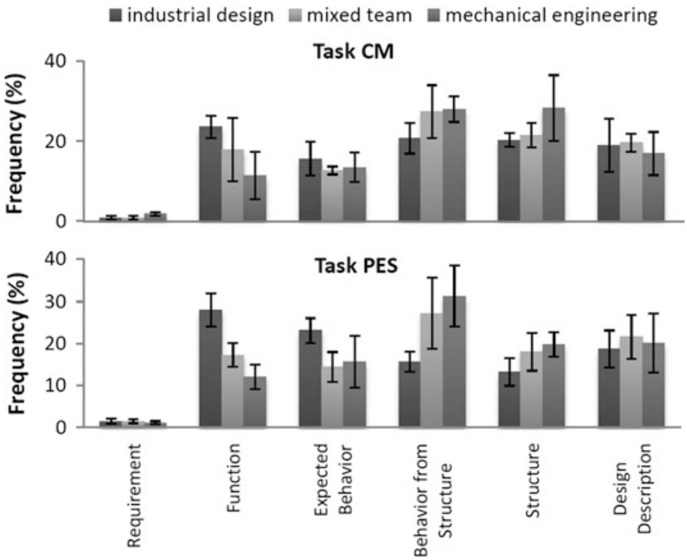


Fig. 4.21 Distribution of design issues (%)

ID sessions had the highest percentages of function issues followed by the Mixed sessions and then the ME sessions. ID sessions also had higher percentages of expected behaviour issues than these other two groups. ME sessions had the highest percentages of the solution-related issues and ID sessions had the lowest ones. For inter-task comparisons, Task PES tended to have more function and expected behaviour issues than Task CM, whereas the percentage of structure issues in Task CM was higher than that in Task PES.

Problem-Solution Indexes of the Whole Sessions

The values of P–S index for each design session are shown in Table 4.17. The problem-focused sessions are highlighted by bold fonts. The results are also aggregated and charted in Fig. 4.22, against a line at the value of 1.00 for the P–S

Table 4.17 Values of P–S index

Groups	Value of P–S index for each team				Mean	SD
	1	2	3	4		
ID CM	0.90	**1.01**	**1.13**	0.88	0.98	0.11
ID PES	**2.04**	**2.32**	**1.74**	**1.40**	1.88	0.39
Mix CM	0.95	0.36	0.89	0.53	0.68	0.28
Mix PES	0.48	0.76	0.77	**1.01**	0.76	0.22
ME CM	0.28	0.34	0.55	0.80	0.49	0.23
ME PES	0.56	0.75	0.46	0.54	0.58	0.12

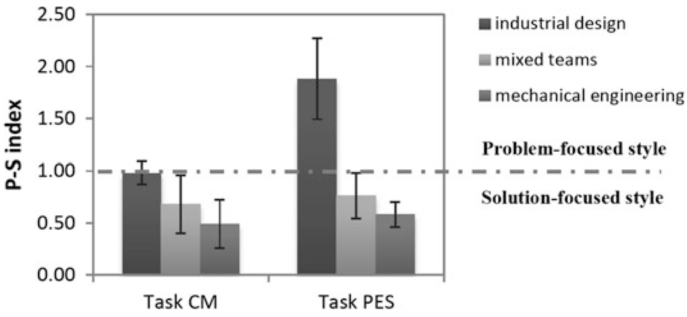


Fig. 4.22 Aggregated P–S index values and metacognitive design style

index signifying the boundary between problem-focused and solution-focused metacognition design styles.

ID PES sessions had significant higher P–S index values than other sessions, demonstrating a strong tendency of focusing on problem-related issues. The P–S index value of the ID CM sessions are around the threshold of problem-solution division. ID teams generally focused more on the design problem than did the mixed and ME teams.

Problem-Solution Indexes in Two Halves

Dividing the design sessions into two halves provides a more nuanced basis to study metacognition—how participants' cognitive effort occurs over time within a design session. Figure 4.23 compares the P–S index values of the two halves with the respective teams. Using Mann–Whitney U tests and Wilcoxon signed ranks test, the results of P–S indexes differences among disciplinary teams are summarized in Table 4.18.

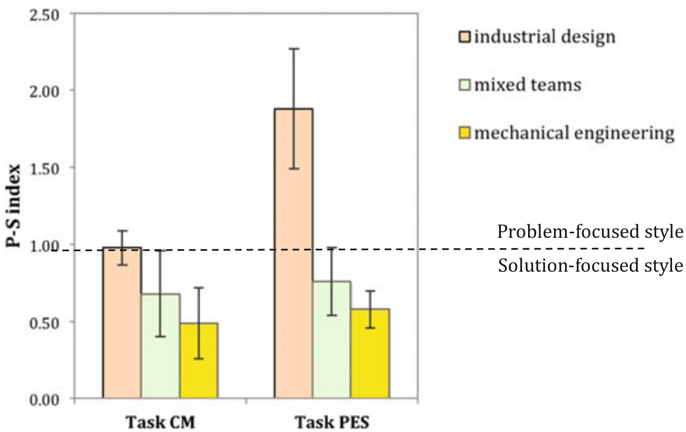


Fig. 4.23 Comparing P–S index of the two halves

Table 4.18 Inter-session comparisons of P–S indexes in the fractioned protocols

Group	First half of design session	Second half of design session
ID teams	ID CM ≈ ID PES	ID CM < ID PES
Mixed teams	Mix CM ≈ Mix PES	Mix CM ≈ Mix PES
ME teams	ME CM ≈ ME PES	ME CM < ME PES
Task CM	ID CM > Mix CM ≈ ME CM	ID CM ≈ Mix CM ≈ ME PES
Task PES	ID PES > Mix PES > ME PES	ID PES > Mix PES ≈ ME PES

≈Not significantly different
>Significantly larger than
<Significantly smaller than

The results suggest that industrial design student teams have a metacognitive design style that is more focused on the design problem than mechanical engineering student teams in both design tasks in the first half of the session. Overall the P–S index dropped in the second half the session.

4.5 Conclusions

This chapter has applied the proposed ontological coding scheme presented in Chap. 3 to multiple cases. Linkography has been used to derive FBS processes. Many coding schemes have been developed for use with design protocols. All such schemes are based on particular views of the activity of designing. Many of these schemes are unique to the data to which they are applied. This limits the applicability of the results obtained. Where more general codings have been attempted they still lack sufficient generality to allow them to be re-used in widely varying circumstances. The use of the FBS ontology and the situated FBS ontology provides a generally applicable coding basis that does not depend on any particular circumstance associated with any unique protocol. The coding scheme does not require that any particular number of designers be involved. It is not limited to any particular stage of the design process, nor is it bound to the face-to-face environment. When it is used to study designers using a computer-mediated environment, especially a 3D environment, the segmentation method needs refinement. However, the principle remains the same.

Figure 4.24 compares the distribution of the FBS processes in the three situations of mechanical engineering students designing using brainstorming, professional architects designing face-to-face and professional architects designing in a 3D-world. The brainstorming session and the face-to-face session exhibit similar patterns of process distributions. The face-to-face session has higher percentages of formulation and reformulation type one, while the brainstorming session has higher

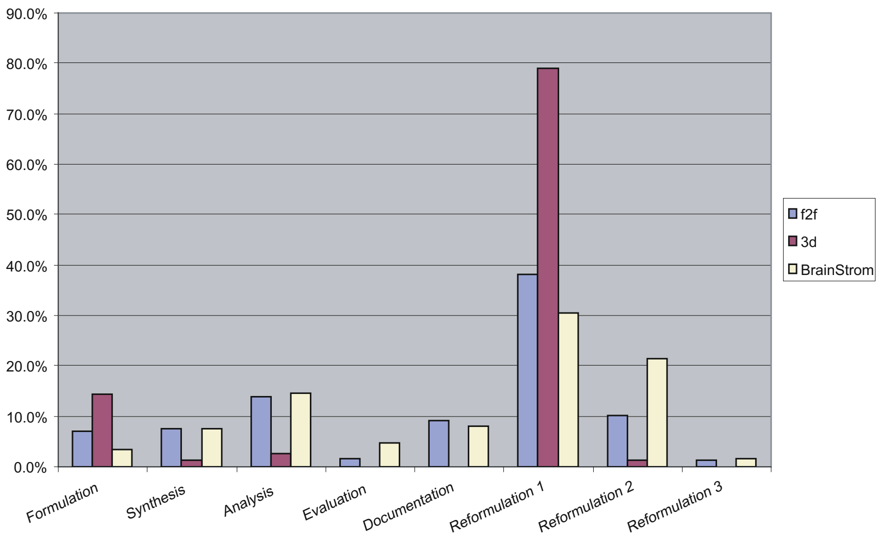


Fig. 4.24 The eight FBS processes of the three sessions

percentages of reformulation type two and evaluation. We can also include the FBS design processes in the 3D-world session, Fig. 4.24.

Figure 4.25 compares the probabilities of each issue in these three sessions. The length (time) for analysis of the face-to-face session is the same as that of the 3D-world session; however, the length of the brainstorming session is four times longer.

From the qualitative analysis we can observe that the designers referred more frequently to the requirements at the beginning of a session. This is reflected by the brainstorming session having the lowest probability of R code. The brainstorming session was more behaviour oriented (higher probability of B codes) while the face-to-face and 3D-world sessions were more structure oriented (higher probability of S codes). The results presented in these cases demonstrate that the ontological approach of coding, together with linkography can be used to study a team of designers and designers using different types of communication channels. These provide a common platform to analyse and compare design activities in various circumstances.

These quantitative models contain considerable detail about the behaviour exhibited in a particular design session. This information can be used to elucidate chronologically-based design behaviour in an individual design session. This can be done by fractioning the design session into halves, thirds, quarters, deciles, etc., treating each fractioned sub-session as a complete session and carrying out the analyses on them. This allows for comparisons of cognitive behaviour across the time.

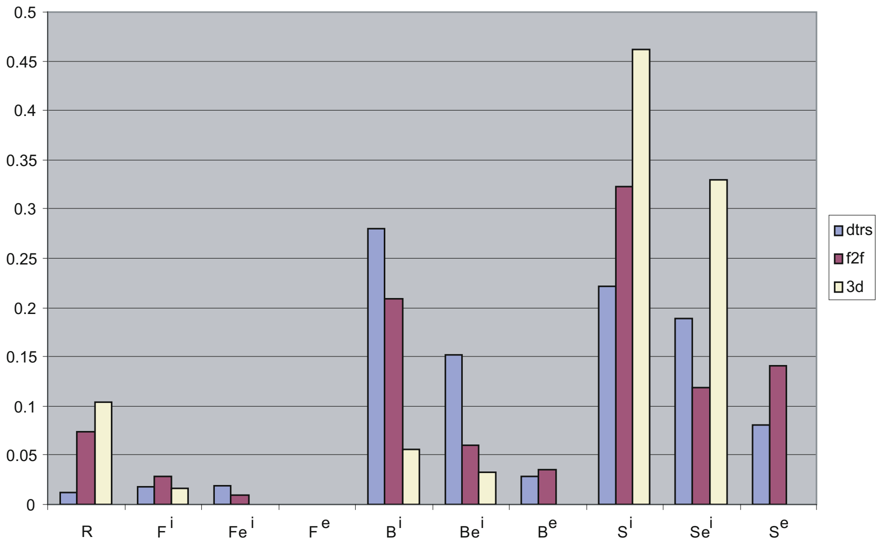


Fig. 4.25 The Markov probabilities of each issue (using the situated FBS coding) of the three sessions

By aggregating results from a set of similar designers, Quantitative models can be used to produce statistically testable results across multiple cohorts. These results can then be compared with aggregated results from design sessions carried out under different conditions to determine the effect of changing design conditions.