Using the FBS Ontology to Capture Semantic Design Information in Design Protocol Studies

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Abstract
This paper presents a method to capture semantic information from design protocols independently of the number of participants. The paper reports on a preliminary study that analyses a design protocol by using the FBS ontology and derives processes within this ontological framework by employing linkography. The usefulness of this method is examined by applying it to the DTRS7 Engineering 1 protocol (E1) as a case study and the focus is team creativity. The original 1990 FBS ontology captures 58% meaningful processes of all the coded processes, while the situated FBS ontology captures 84% meaningful processes of all the coded processes. Further coding analysis may improve this percentage. The session is characterized, according to the ontology, by the high percentage of behaviour reformulation, followed by structure reformulation, and analysis. This ontologically-based coding provides opportunities to understand and compare design protocols in a uniform manner independent of discipline or number of designers.

1. Introduction

The Delft 1994 workshop (Cross et al 1996) showed there is a variety ways of coding scheme that can be applied to study the same design protocol; these help to gain a rich understanding of different aspect of designing. However, the diversity and uniqueness of each scheme makes it hard to reuse and compare protocol results either qualitatively or quantitatively. The motivation behind this paper is to develop a general coding scheme that yields high quality, uniform results, that maps well to the behaviour of designers, so as to have a deeper understanding of design thinking and activities. The general coding scheme is based on an ontology of the design domain and as a consequence is not an ad hoc development specific to a unique protocol but one that can be used uniformly across design protocols independently of the specific design activity being studied and unrelated to the number of participants in a design team.

This paper explores the use of the FBS ontology to develop a general coding scheme to study designing. Its aim is to capture semantic information from design protocols. This semantic information can then be utilized: 1) to explore different aspect of designing according to the focus of interest; 2) to locate different types of design transformation processes. In this section a brief summary of the FBS framework with its relation to design and design creativity is presented.

The FBS ontology framework (Gero 1990) models designing in terms of three basic classes of variables: function, behaviour, and structure. In this view the goal of designing is to transform a set of functions into a set of design descriptions (D). The function (F) of a designed object is defined as its teleology; the behaviour (B) of that object is either derived (Bs) or expected (Be) from the structure, where structure (S) is the components of an object and their relationships. A design description never gets transformed directly from the function but undergoes a series of processes among the FBS variables. Figure 1 shows the relationships among the eight transformation processes and the three basic classes of variables.

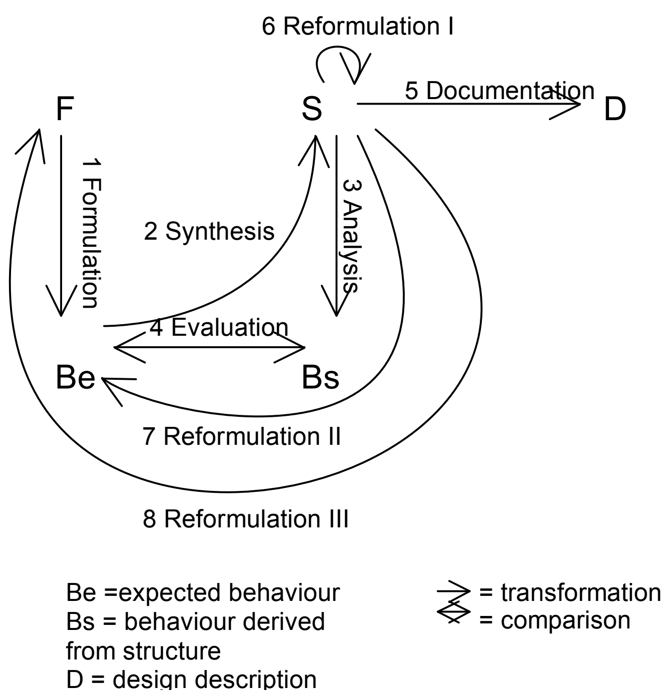


Figure 1. The FBS ontology of designing

There are various definitions of creativity in different fields (Taylor 1988). In the design field, creativity has long been one of the most important criteria when measuring the artifact. Creativity is always associated with terms like 'originality' and 'novelty'. In designing it also connotes utility and unexpectedness. Human creativity can be considered as being related to cognitive processes that generate novel ideas within a relevant context. Boden (1991) introduced "historical" creativity and "psychological" creativity to differentiate the social-historical creativity from the individual creativity. Suwa et al. (1999) added the term "situated creativity" to identify creativity during the process of designing rather than considering the outcome. Under the FBS framework situated creativity is defined as the introduction of new variables in relation to the intention of the artifact being designed. New variables are introduced in the reformulation processes; structure, behaviour and function can all be part of reformulations. Therefore, under this framework the formulation and reformulations are vital for creativity. Situated creativity is a fundamental design activity and it can be claimed to be one of the distinguishing features of designing.

2. DTRS7 Engineering 1 Protocol

The DTRS7 Engineering protocol is divided into two episodes; the first one concerns the problem of keeping the print head in contact and the optimum angle with the media despite wobbly arm moment. The second episode deals with protecting the print head from abusive use and overheating. The first episode concerns generating ideas from available products that follow a contour. Several products were mentioned such as: a sledge, snowboard, windsurf board, shaver, snow mobile, train, and slicer. Other concepts such as wheels, spirit level, and laser leveler were also discussed. Loosely related to those analogies, a few proposed shapes, such as mouse-type pen, were proposed. Besides product behaviour, user behaviour was also considered.

3. Coding Scheme

The coding scheme consists of the FBS classes – five codes labeled 1 through 5 in Figure 1 and two additional codes: requirement (R) and others (O) that did not fit within these codes. Below are some examples from the protocol for each code.

Example of requirements:

> "quite important is its about the thermal-incli- inclis ( ) pen" (E1, 43)
> "design a-a prototype" (E1, 56-57)

Examples of function:

> "that's the standard plain thermal paper err and then it can draw" (E1, 54)

Examples of expected behavior:

> "either atoms or line types" (E1, 55)
> "we can print thermo reactive dyes onto media substrates" (E1, 68)

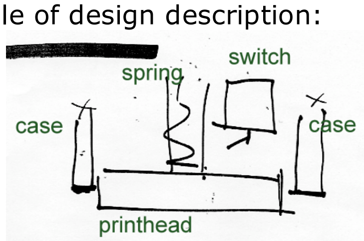
Examples of behavior:

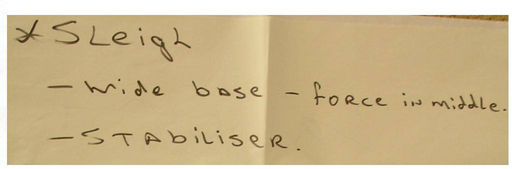
> "it'll be about fifty percent more expensive" (E1, 199)
> "if you lift an optical mouse slightly off the page you'll see the pattern it creates" (E1, 672 674)

Examples of structure:

> "a sledge or a snowboar- a skis or snowboard" (E1, 150)
> "show the relative size of the pen if you've got an example" (E1, 171)

Example of design description:





Examples of others:

> "yeah we'll come to that in a minute" (E1, 737)

3.1 Coding Segments

The protocol is segmented strictly according to the ontology – each segment contains only one class of FBS code. The segmenting and coding are done simultaneously by discerning whether an action or utterance expresses the FBS aspect of designing or is concerning the requirements or others. If an utterance contains more than one class it will be divided. This also apply to the 'O' and 'R' code. Drawing and writing actions are also considered as segments of structure. By doing this, the segments will not have a fixed duration and are usually very short, typically in the magnitude of seconds.

The two episodes are about the same length, 57 minutes each. This study will use only the first episode as an illustration. We disregard the first 5 minutes as it involves the management of the meeting rather than the design process. The protocol is coded twice by the same coder with a ten days separation and then arbitrated. The agreement of codes is over 86%. Within the 52 minutes in the first episode we coded 475 segments. The average segment length is about 6.5 seconds. Of the 475 segments 445 segments have FBS codes; those segments without FBS codes (30) consist mostly of jokes or communications that are not related to the design process or the resulting artefact. Figure 2 shows the percentages in each of the FBS categories. The highest percentages are in the structure and behaviour classes. In this protocol these high percentages are due to the frequent use of analogies with other products and situations.

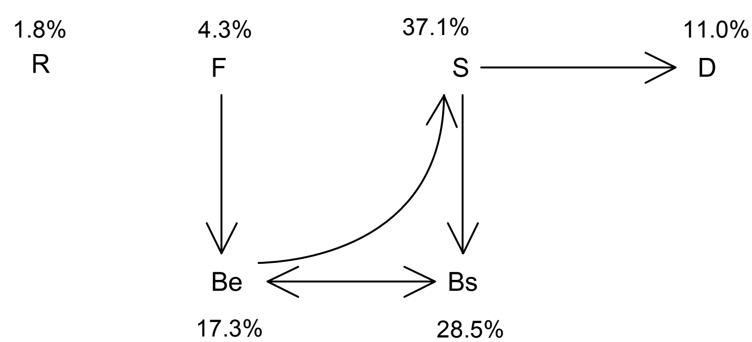


Figure 2. Percentages of each code

3.2 Linking the segments

The connections between the segments, independent of the code, are discerned by using Goldschmidt's (1990) linkography technique. Figure 3 shows part of the linkograph of this session with the chunks, clusters of links, being labeled.

There are 1,143 links among the 475 segments, so on average each segment has about 2.4 links. However, some segments have many more links than others. Table 1 compares the distribution of the codes of the segments with the occurrences of codes in the links. The bar charts in Figure 4 show the percentages of segments and links with the FBS code. Compared to the coded segments it can be observed 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 the expected requirement, behaviour, and structure segments in this session are more influential. The statistics of 1990 FBS coding, as for Gero and McNeill (1998) and McNeill et al (1998), do not reflect this.

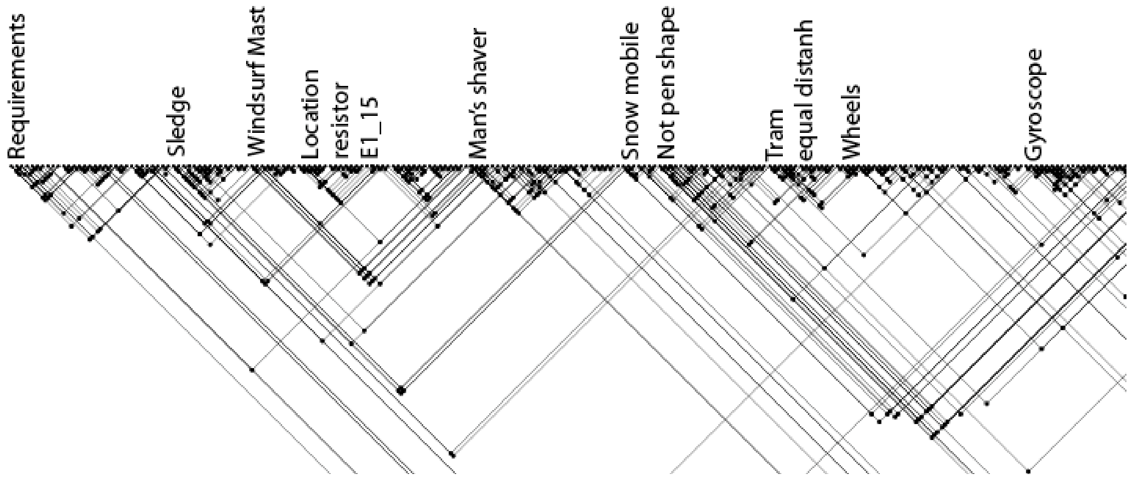


Figure 3. Part of the linkograph of the segmented protocol

Table 1. Comparing the distribution of codes in segments and links

Code	Segment		Links	
R	8	1.8%	71	3.2%
F	19	4.3%	75	3.3%
Bs	127	28.5%	560	24.9%
Be	77	17.3%	455	20.2%
S	165	37.1%	887	39.5%
D	49	11.0%	200	8.9%
Total	445	100%	2248	100%

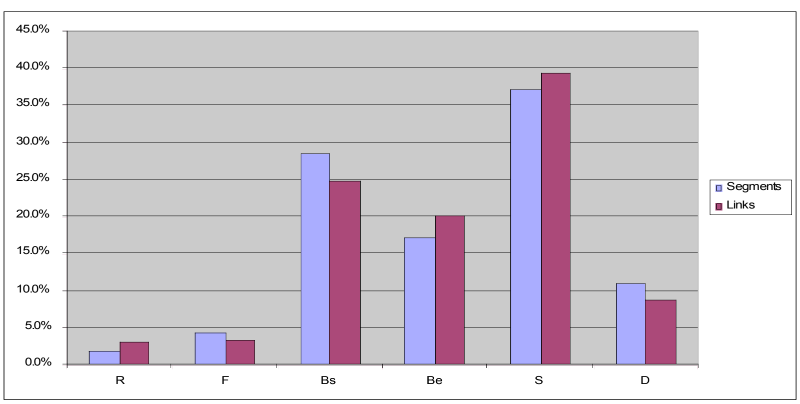


Figure 4. The percentages of each code for segments and links

4. Deriving FBS processes from coded segments and links

In the following analysis, we use the symbol ">" to denote the link or the transformation between the nth and the $(n+i)^{th}$ segments. For example when the nth segment is coded as S (structure) and the $(n+i)^{th}$ is coded as D (description); and if they are linked, we use S>D to represent this link. In this example, we view this as the documentation process, transformation from structure to design description.

The 1,143 links are viewed as design processes. The linkograph become a network of transformation processes. There are 7 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 meaning. Table 2 shows the FBS related processes derived from the links of the coded segments. There are 34 types of FBS processes being recorded; those FBS processes in the framework are represented in Table 3.

Table 2. Percentages of all the processes derived from codes and links

Requirement		Function		Behaviour		Expected Behaviour		Structure		Description	
R>S	1.5	F>S	0.5	Bs>S	7.6	Be>S	7.2	S>S	17.7	D>S	3.7
R>R	0.5	F>F	1.3	Bs>F	0.3	Be>F	0.3	S>F	0.6	D>F	0.1
R>F	0.2	F>D	0.2	Bs>D	1.4	Be>D	1.9	S>D	5.0	D>D	1.4
R>Be	1.3	F>Bs	0.6	Bs>Bs	7.4	Be>Bs	5.1	S>Bs	11.8	D>Bs	2.2
R>Bs	1.4	F>Be	1.2	Bs>Be	4.1	Be>Be	6.1	S>Be	5.8	D>Be	1.0
				Bs>R	0.1	Be>R	0.1	S>R	0.3		

Table 3. Percentages of the 8 FBS processes

Processes		Occurrence	Percentage
Formulation	R>F,F>Be	15	1.4
Synthesis	Be>S	80	7.2
Analysis	S>Bs	131	11.8
Documentation	S>D	55	5.0
Evaluation	Be<>Bs	57(Be>Bs), 46(Bs>Be) 103	9.3
Reformulation I	S>S	196	17.7
Reformulation II	S>Be	64	75.8
Reformulation II	S>F	7	0.6
	Total	651	58.7

We have defined situated creativity as based on formulation and reformulations. In this episode, the reformulations are mostly of structure and behaviour.

The following are examples for the reformulation of structure and behaviour: analogy the structure of other products, like sledge, windsurf mast; considering the thermal pen in the shape of other things instead of a pen; using a universal joint to keep the angle; using springs or stabilizers to keep it level. Suggestion of the locations of resistors (E1 190) prompts the responses of the cost (E1 195, 199) is another example of reformulation of behaviour.

The reformulation of function is rare which reflects the nature of this session – mechanical brainstorming for ideas to keep the thermal pen in contact with the media at a correct angle. Some of the function aspects are deliberately not dealt with. For example in E1, 622 to 623 "could we sorry could we actually see what they're doing I mean are they drawing pictures or making invitations or Christmas cards or-" as in E1, 624 "erm ( ) we're going to try to deal with that a fair bit on Monday".

The 1990 FBS ontology covers more than half of the processes derived from the links of the coded segments. What are the other processes? Does that reflect the deficiency of this ontology? Some of the most frequent processes are: Bs>S (7.6%), Bs>Bs (7.4%), Be>Be (6.1%), S>Be (5.8%), D>S (3.7%), and D>Bs (2.2%).

Reviewing the protocol, the large scale of the granularity fails to pick up the Be in the Bs>S processes. If the granularity were finer, there should be an expected behaviour before the structure code. For example the segment in E1, 141: "the sledge manages to keep level by having quite a wide base" is coded as Bs because it analyzes an existing product to get the behaviour that the design can borrow. This segment is linked to a sequence segment in E1, 153-156: "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 is coded as structure because it proposed a structure of using stabilizers. The idea of sledge, the behaviour of wide base, is translated to expected behaviour of wide base which leads to the expected structure of stabilizers.

The F>F and Be>Be can be viewed as reflections of function and behaviour in many cases; the D>S is the interpretation of depicted structure. The Bs>Bs usually is a result of further analysis. The Be>D is the depiction of behaviour, for example the segment: "and then you have the weight right in the middle so they manage to keep both runners on the snow" (E1, 147) is coded as expected behaviour which is linked to the following segment: "[write: force in middle]" which is a depiction of behaviour description. These transformations are meaningful processes resulting from the interactions among members and artifacts. In order to veridically capture these, we turn to the situated FBS framework (Gero and Kannengiesser 2002) and recode this episode.

5. Situated FBS Coding

There are new concepts that constitute the situated FBS framework or ontology: the notion of situated cognition introduced by Clancey (1997); the idea of constructive memory based on Dewey's (1896) and Bartlett's (1932) work; and the observation of designing as an "interaction of making and seeing" by Schon and Wiggins (1992). Gero and Kannengisser (2002) developed these ideas further and integrated them into the FBS ontology to form the situated FBS framework by introducing interactions among three worlds – the external, interpreted, and expected worlds. An agent or human interacts and understands the external world through his interpretation of the external world to form memories of his interpreted world. In order to change the external world (the act of designing) he "focuses" to transform experiences to produce the expected world before taking action in the external world. In this framework the original eight processes are increased to twenty to allow for these additional activities, Figure 5.

Table 4 relates the twenty situated FBS processes to the original eight processes (Gero and Kannengiesser 2002). Of particular interest are the formulation and reformulation processes in this framework. The formulation process involves: the interpretation of requirements (R) in terms of Fi, Bi, and Si representations (processes 1, 2 and 3); reflecting, based on experience, on those representations (processes 4, 5 and 6); focusing on subsets on these internalized requirements (processes 7, 8 and 9); and process 10 that corresponds to the original formulation in the FBS framework. The focusing and reflecting (processes 4 to 9) appear in all the three types of reformulations. Reformulations II and III are not limited to be driven by structure alone but also by external representation of function (Fe, process 20) and behaviour (Be, process 19) as well.

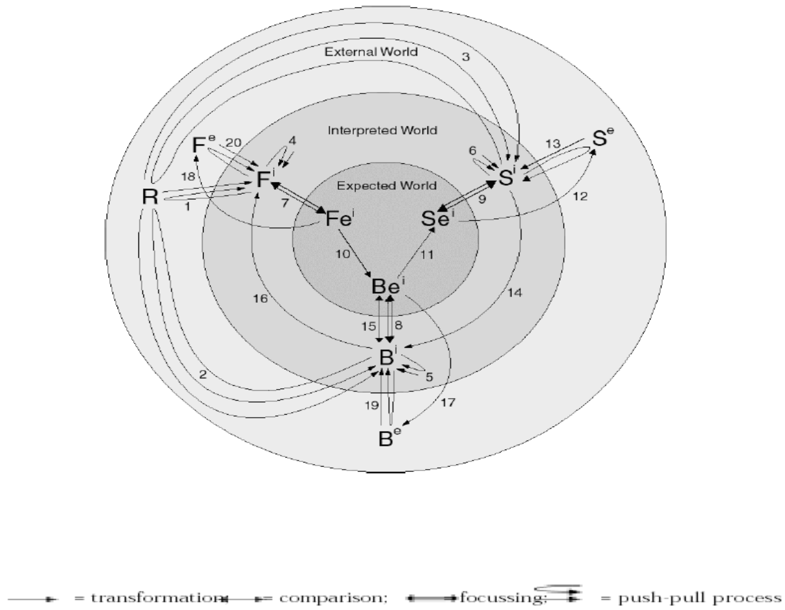


Figure 5. The situated FBS ontology (Gero and Kannengiesser 2002)

Table 4. Relating the 20 situated FBS processes to the original 8 FBS processes

Formulation	1, 2, 3, 4, 5, 6, 7, 8, 9, 10
Synthesis	11, 12
Analysis	13, 14
Evaluation	15
Documentation	12, 17, 18
Reformulation I	6, 9, 13
Reformulation II	5, 8, 14, 19
Reformulation III	4, 7, 16, 20

With the introduction of new classes of variables the new coding scheme is shown in Table 5. For ease of comparison, the segments have not been refined so the total numbers of segments and total number of links will be the same.

Table 5. Coding categories correspond to situated FBS ontology

R:	requirements derived from the given brief
F^i:	interpreted function either derived from requirements or ascribing meaning to depicted structure
Fe:	external representation of function, usually in terms of written words (not seen in this session)
Fe^i:	expected function resulted from focusing on Fi
B^i:	interpreted behaviour from depicted structure or requirements
Be:	external representation of behaviour, usually in terms of written words
Be^i:	expected behaviour derived from expected function or interpreted behaviour which result from requirement or interpreted structure

S^i:	interpreted structure either from external structure or from requirement
Se:	depiction that indicates structure
Se^i:	expected structure sometime without depiction

Table 6 shows the distributions of codes in the segments and links and their percentages. There is no documentation of function. For clarity and ease of analysis the interpretation and reflection categories of processes are separated from the formulation and reformulation processes so that there is no overlapping of processes in any of the categories. Figure 6 shows the percentages of the each code of segments and links using the situated FBS ontology. 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 function, and the depiction of behaviour are of less important than they appear in the segments.

Table 6. Comparing the distribution of codes in segments and links

	Segments		Links	
R	8	1.8%	71	3.2%
F^i	10	2.2%	33	1.5%
Fe	0	0.0%	0	0.0%
Fe^i	9	2.0%	44	1.9%
B^i	127	28.5%	560	24.9%
Be	11	2.5%	32	1.4%
Be^i	77	17.3%	455	20.2%
S^i	105	23.6%	544	24.2%
Se	38	8.5%	168	7.5%
Se^i	60	13.5%	343	15.3%
Total	445	100.0%	2248	100.0%

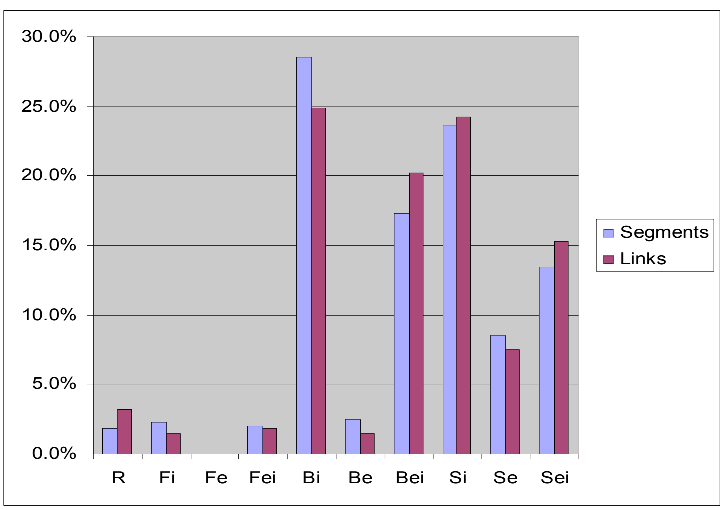


Figure 6. The percentages of the each code of segments and links in the situated FBS framework

Using the situated FBS variables as the codes and then aggregating them into the basic 8 design processes plus the interpretation of the requirements gives us an 84% coverage of the segments, Figure 7. 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.

Table 7. Percentages of situated FBS processes

Interpretation of requirement	1, 2, 3	4.4%
Formulation	10	1.2%
Synthesis	11	8.8%
Analysis	14	15.6%
Evaluation	15	5.1%
Documentation	12, 17, 18	6.0%
Reformulation I	6, 9, 13	20.9%
Reformulation II	5, 8, 19	20.1%
Reformulation III	4, 7, 16, 20	1.7%
Total		83.9%

6. Discussion

The FBS ontology denotes fundamental processes of designing that are general enough to embrace almost all design situations. Unlike most coding scheme, supported by available protocol analysis software, which allow 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 study of the interaction among the FBS classes and processes may help to deepen the understanding of designing which can then inform the development of tools that aid designing at different stages.

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 84% of all designing activities in this protocol. The coverage is expected to improve as this is only the first pass of a two-pass process that could not be completed in the time available for this draft reporting.

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. It is claimed that 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 FBS-based coding scheme has previously been used with individual designers (Gero and McNeill 1998) and the results presented in this paper demonstrate that it can be used with a team of designers. 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.

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