# Measuring Cognitive Design Activity Changes During an Industry Team Brainstorming Session

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This paper presents the results of using an ontologically-based method of measuring cognitive design issues and design processes on an in-situ team brainstorming session to study the changes in cognitive design issues and design processes at the beginning, middle and end of the session. Detailed results of the distributions of issues and processes are presented.

## Introduction

This paper uses an ontological view of understanding design cognition. The ontological view consists of issues and processes. It is assumed that designers use different cognitive resources for different design issues and different design processes, and that they use different cognitive resources to handle the states before and after any design processes. This ontological view is used to analyse a protocol of a design session of a team of designers from industry brainstorming.

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## Quantifying Design Processes

In order to establish a common ground to study design activities, an established ontology from the literature is used as an overarching principle to guide the protocol study.

### The FBS Ontology

The research commenced with the following statement about designing:

> "The meta-goal of design is to transform requirements, more generally termed functions which embody the expectations of the purposes of the resulting artefact, into design descriptions. The result of the activity of designing is a design description." [1]

This view centers design around the creation of artefacts, whether physical or virtual. Anything that is not related to the resulting artefacts is not considered within this framework. For example, supporting activities such as planning and scheduling are not included. People can spend all their time planning and scheduling without producing any design description.

The FBS design ontology [1], as a formal model, models designing in terms of three fundamental classes of issues: function, behavior, and structure; along with two external classes: design descriptions and requirements. In this view the goal of designing is to transform a set of functions into a set of design descriptions. The function (F) of a designed object is defined as its teleology; the behavior (B) of that object is either its expected behavior (Be) or behavior derived from the structure (Bs), where structure (S) are the elements and their relationships that go to make up the artefact. A design description cannot be transformed directly from the functions, which undergo a series of processes among the FBS issues. Figure 1 shows the relationship among these issues with the resulting processes that link the issues.

Formulation (F→Be) is the transformation of the function issues of a design into issues of expected behavior. Synthesis (Be→S), is the transformation of the expected behavior issues (Be) into structure issues of the artefact that aim to satisfy the requirements. Analysis (S→Bs) is the derivation of "actual" behavior issues from the synthesized structure (S). Evaluation (Bs←→Be), is the comparison of the actual behavior (Bs) with the expected behavior (Be) to decide whether the artifact is to be accepted. Documentation (S→D), is the production of any design description from structure issues of the designed artefact.

Traditional models of designing reiterate the analysis -synthesis - evaluation processes until a satisfactory design is produced. In the FBS ontolo-

ontology, Figure 1, three types of reformulations is introduced to expand the design state space so as to capture the innovative and creative aspect of designing, which have not been well articulated in most models because they have not been adequately understood.

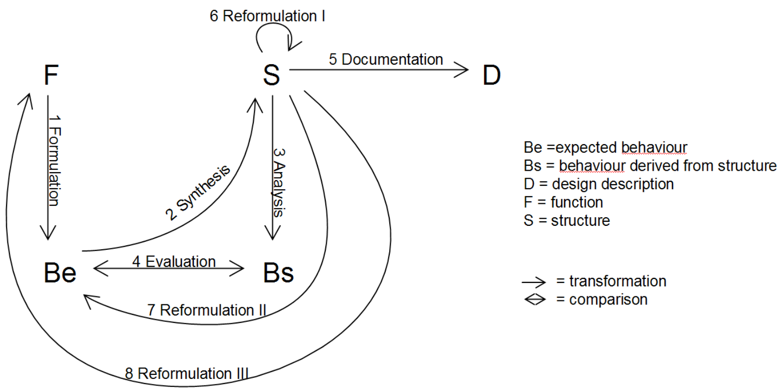


**Fig. 1** The FBS ontology of designing

Reformulation type I (S→S'), addresses changes in the design state space in terms of structure issues. Reformulation type II (S→Be'), addresses changes in design state space in terms of behavior issues. A review of synthesized structure may lead to the addition of expected behavior variables. Reformulation type III (S→F'), addresses changes in design state space in terms of function issues.

## The Brainstorming Session

Data for a brainstorming design session was obtained from the 7$^{th}$ Design Thinking Research Symposium [2]. The source data was a video of design meetings taking place in a product design practice. The data is made up of a 4-camera video recording, Figure 2, and the transcripts of the voice communication. The team consisted of a business consultant, who acted as the moderator (Allan), three mechanical engineers (Jack, Chad and Todd), an electronics business consultant (Tommy), an ergonomicist (Sandra), and an industrial design student (Rodney). They were all from the same company and the student, Rodney, was on an internship with the company.

In this brainstorming session, the team was asked to provide ideas for solving technical issues of a working demonstrator of a thermal printing pen. The two main issues were: 1) keeping the print head in contact with the paper surface and optimum angle with the media despite wobbly arm moment; and 2) protecting the print head from abusive use and overheating. Observing the protocol, it can be divided into two episodes corresponding to these two primary concerns. The video and the transcript of the utterances formed the basis of a think-aloud protocol [3], [4].

The remainder of the paper commences with a brief qualitative description of the design session and is followed by sections on quantitative measurements of the cognition of the design activity. The quantitative sections commence with the word counts and turn taking of the team members. This is followed by a more detailed analysis based on the FBS ontology issues and processes coding scheme.

## Qualitative Observations

The whole session lasted about one hour and thirty-five minutes. The session can be divided into two episodes; the first one concerned the problem of keeping the print head in contact and at the optimum angle to the media, despite wobbly arm moments. 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, snowmobile, train, and slicer. Other concepts such as wheels, spirit level, feedback to user, and laser leveler were also discussed. Loosely related to those analogies, a few shapes, such as a mouse-type pen, were proposed. Besides product behavior, user behavior was also considered.

In the second episode, ways of protecting the print head were discussed. A sheath protecting the print head was proposed, the idea of a viscous damper such as leaky syringe was discussed. Other ideas like spring loaded cap, dead man's handle and a dock or cradle, that provides cleaning and charging when the pen is not in use were also discussed. Sandra left about thirty minutes before the end of the session.

## Quantitative Observations

This section quantifies some of the qualitative observations in terms of word count and turn taking.

### *Word Count and Turns Variation during the Session*

This section commences with the total number of words and turns in five minutes intervals across the session, Table 1, published by Gero and Kan [5]. Figure 2 is the corresponding trends of word count and turns.

**Table 1** Total number of words and turns in five minutes intervals [4].

| **Interval** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** |
|---|---|---|---|---|---|---|---|---|---|---|
| **Total no. words** | 907 | 863 | 828 | 761 | 830 | 700 | 804 | 800 | 758 | 845 |
| **Total no. turns** | 21 | 61 | 78 | 63 | 74 | 45 | 68 | 77 | 84 | 94 |
| **Interval** | **11** | **12** | **13** | **14** | **15** | **16** | **17** | **18** | **19** | |
| **Total no. words** | 786 | 717 | 766 | 782 | 684 | 717 | 700 | 738 | 810 | |
| **Total no. turns** | 88 | 91 | 84 | 93 | 59 | 46 | 63 | 94 | 109 | |

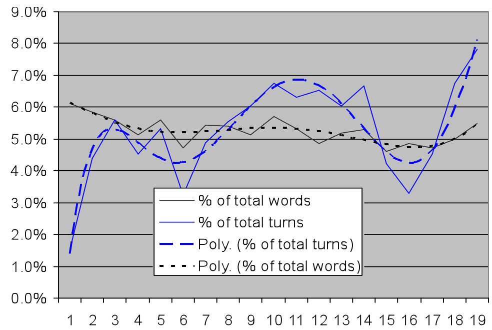


**Fig. 2** The percentages of total words and total turns in five minutes intervals for the entire team, “Poly” is the polynomial line of best fit [5].

Looking at the team as a whole their percentages of interactions increased but their number of words remained fairly constant. This may indicate they have learned by producing a shared mental model [6], which is implied by the increased interaction with each interaction requiring fewer words to communicate.

### *Word Count and Turns of Groups*

The group of mechanical engineers was the biggest group with the same background. Since they belong to the same design profession, it is expected that they will share similar mental models, hence their conversation may display a common pattern. However, neither the curves in Figure 3, nor a statistical analysis, suggest any correlating patterns.

Todd was the most active participant in this group based on the word count. Figure 4 shows that the word count curves of Todd and Tommy are of similar shape from the 2$^{nd}$ interval until the 17$^{th}$ interval; they seemed to form a cross-discipline sub-team.

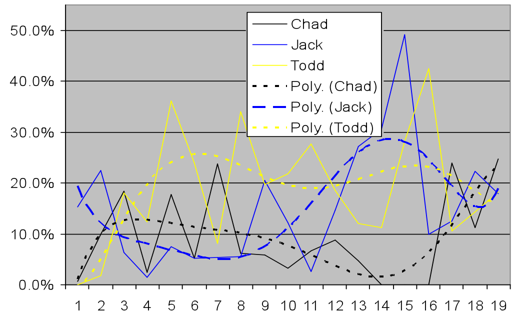


**Fig. 3** The percentages of word count of the three mechanical engineers in a five minutes interval [5]

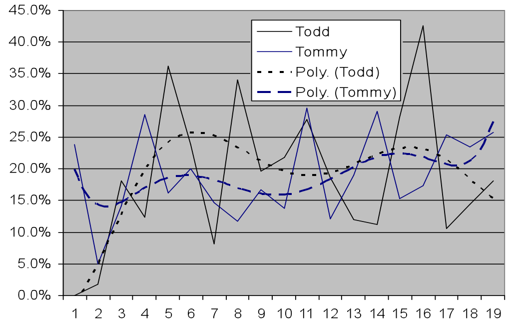


**Fig. 4** The percentages of word count of Todd and Tommy [5]

## FBS Segmenting and Coding

The brainstorming protocol is segmented and coded strictly based on these six categories of issues according to the following rule: one segment per code/ one core per segment. This deals with the problem of how many codes should there be to a segment. Those utterances that do not fall into these categories were not coded.

### Results

This section presents the statistical results of the FBS coding that quantifies the protocol into issues in terms of FBS. Two remotely-located independent coders segmented and coded the sessions and arbitrated through internet telephony. The inter-coder agreement was over 80% and each coder’s agreements with the arbitrated set was over 88%. Table 2 shows examples of each code.

**Table 2** Examples of coding

| | |
|---|---|
| **R** Requirements | “quite important is it’s about the thermal-incli-inclis ( ) pen” |
| **F** Function | “I mean it only moves in one axis that’s the standard plain thermal paper err and then it can draw” |
| **Be** Expected Behavior | “so there needs to be this contact maintained” |
| **Bs** Behavior from Structure | “ I mean it only moves in one axis ” |
| **S** Structure | “a sledge or a snowboard a skis or snowboard” |
| **D** Design Description | (write: sledge) |
| Not Coded | “yeah, we’ll come to that in a minute” |

***Issue Distribution of the Session***

After arbitrating there were 1,280 segments that contained FBS issues. Table 3 summarizes the counts and percentages of each issue.

**Table 3** Count and Percentage of Issues

| | F | Be | Bs | S | D |
|---|---|---|---|---|---|
| Count | 47 | 275 | 369 | 512 | 77 |
| Percentage | 4.0 | 21.0 | 29.0 | 40.0 | 6.0 |

The percentages of FBS issues reflect the nature of the session – they were mainly borrowing behavior and structure of other objects. The behavior issues occupied half of the counts followed by structure. The low count of D was because only shared documentations were coded. Not withstanding the nature of the session, functional aspects were discussed.

The percentages in Table 2 only give an account of the whole session, however according to Asimow elementary model [7], design can be characterized by a series of cycles through analysis of the problem, synthesis of a solution, and evaluation of the solution. If Asimow's model is mapped onto this ontology, the analysis of the problem will involve function issues; the synthesis of solution will involve structure issues and the evaluation of solution will involve behavior issues. To observe Asimow's cycles of designing the number of the FBS issues needs to be counted within a sequence.

In the next sub-section, the contribution of FBS issues over the session will be presented. Results are also presented that differentiate the contribution of individuals and sum them for the whole team.

***Distribution and Variations of FBS Issues***

In order to obtain a more fine-grained understanding of how the issues are distributed, a window of 128 segments is taken and moved segment by segment from the beginning to the end of the protocol. This produces an averaging of that issue over those segments. With this 128 segments sliding window the number of FBS issues produced by an individual is counted and presented in Figures 6 to 10 for issues F, Be, Bs, S and D respectively. The horizontal axes show segment numbers and the vertical axes show issue counts. In each of the graphs the top surface of the graph shows the overall behavior of the team, while the shading maps onto individual team members.

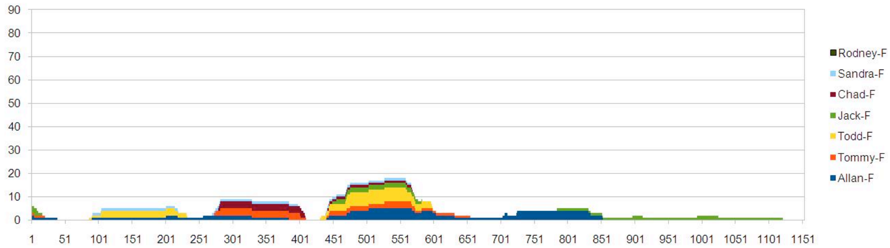


**Fig. 6** F issue distribution of individuals with a 128 segment moving window.

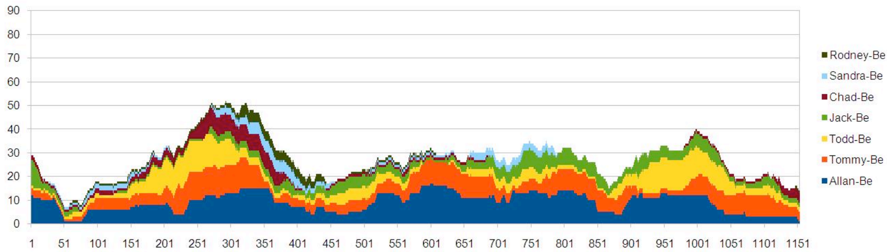


**Fig. 7** Be issue distribution of individuals with a 128 segment moving window.

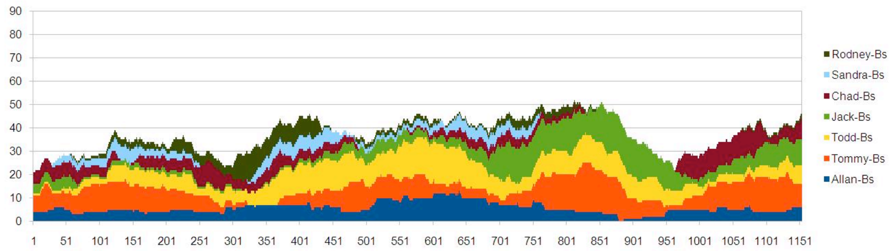


**Fig. 8** Bs issue distribution of individuals with a 128 segment moving window.

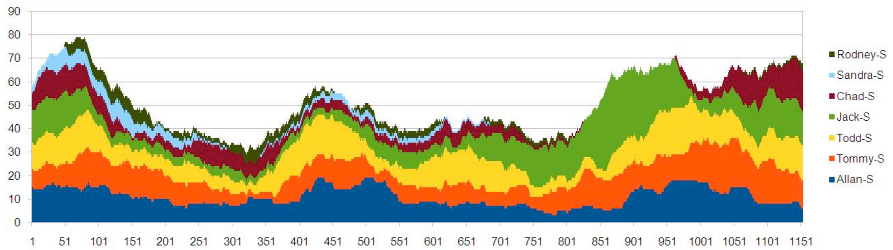


**Fig. 9** S issue distribution of individuals with a 128 segment moving window.

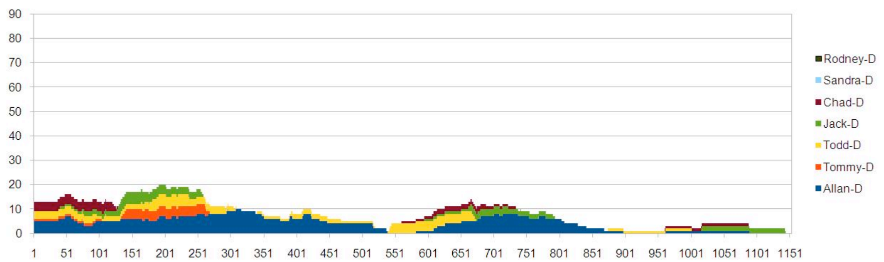


**Fig. 10** D, issue, distribution of individuals with a 128 segment moving window.

As expected in a brainstorming session the structure issue, S, is the dominant issue. Again as expected in a brainstorming session the issues of expected behavior, Be, and behavior from structure, Bs, are relatively low as team members had been advised to suspend judgement. One unexpected result is that the F issues concentrate towards the middle rather than at the beginning of the session as has been observed elsewhere [8].

From Figures 6 to 10, qualitatively it appears that there are changes in distributions across the design session. The significance of the changes is tested by counting the first, middle and last 300 segments of each session, giving us a total sample of 900 issues spread across all members of the team, Table 4 and Figure 11.

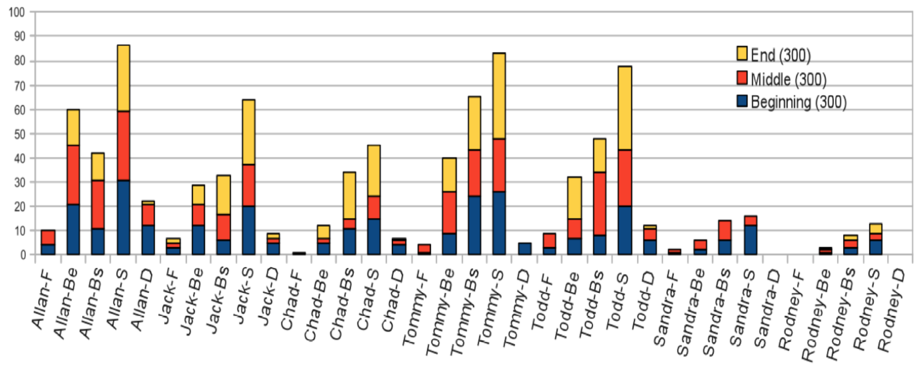


**Fig. 11** The distribution of design issues of individuals within the first, middle and last 300 segments of the session.

**Table 4**. FBS issue variations of individual team members

| | | F | Be | Bs | S | D | Sum |
|---|---|---|---|---|---|---|---|
| **Allan** | First | 4 | 21 | 11 | 31 | 12 | 79 |
| | Middle | 6 | 24 | 20 | 28 | 9 | 87 |
| | Last | 0 | 15 | 11 | 27 | 1 | 54 |
| **Chad** | First | 0 | 5 | 11 | 15 | 4 | 35 |
| | Middle | 1 | 2 | 4 | 9 | 2 | 18 |
| | Last | 0 | 5 | 19 | 21 | 1 | 46 |
| **Todd** | First | 3 | 7 | 8 | 20 | 6 | 44 |
| | Middle | 6 | 8 | 26 | 23 | 5 | 68 |
| | Last | 0 | 17 | 14 | 35 | 1 | 67 |
| **Rodney** | First | 0 | 1 | 3 | 6 | 0 | 10 |
| | Middle | 0 | 1 | 3 | 3 | 0 | 7 |
| | Last | 0 | 1 | 2 | 4 | 0 | 7 |
| **Jack** | First | 3 | 12 | 6 | 20 | 5 | 46 |
| | Middle | 2 | 9 | 11 | 17 | 2 | 41 |
| | Last | 2 | 8 | 16 | 27 | 2 | 55 |
| **Tommy** | First | 1 | 9 | 24 | 26 | 5 | 65 |
| | Middle | 3 | 17 | 19 | 22 | 0 | 61 |
| | Last | 0 | 14 | 22 | 35 | 0 | 71 |
| **Sandra** | First | 1 | 2 | 6 | 12 | 0 | 21 |
| | Middle | 1 | 4 | 8 | 4 | 0 | 17 |
| | Last | 0 | 0 | 0 | 0 | 0 | 0 |

Table 5 shows the results, for each individual member of the team, of two tailed paired-t tests carried out for testing the following:

- FBS issues distribution of the first 300 segments against the same issues in the middle 300 segments,
- FBS issues distribution of the first 300 segments against the same issues in the last 300 segments, and
- FBS issues distribution of the middle 300 segments against the same issues in the last 300 segments.

**Table 5**. Probabilities of paired-t test of individual's FBS issue count

| | First and Middle (p) | Middle and Last (p) | First and Last (p) |
|---|---|---|---|
| Allan paired-t | 0.51 | 0.01 | 0.05 |
| Jack paired-t | 0.55 | 0.25 | 0.56 |
| Chad paired-t | 0.08 | 0.17 | 0.35 |
| Tommy paired-t | 0.77 | 0.54 | 0.66 |
| Todd paired-t | 0.23 | 0.97 | 0.29 |
| Sandra paired-t | 0.69 | N/A | N/A |
| Rodney paired-t | 0.37 | 1.00 | 0.21 |

With paired-t test, the test statistic is $t$ with n-1 degrees of freedom. If the p-value associated with t is low (< 0.05), there is evidence to reject the null hypothesis that the difference between the two observations is zero. Row 1 of Table 4 suggests, with a high probability, that Allens' distribution of FBS issues at the end of the session is different from the middle and start of the session. Other than for Allan, the variations of the distribution of FBS issues in the others are not conclusive.

## Producing Design Processes from a Linkograph

Linkography was first introduced to protocol analysis by Goldschmidt [9] to assess the design productivity of designers. The design protocol is decomposed into small units Goldschmidt called "design moves". Goldschmidt defined a design move as "a step, an act, an operation, which transforms the design situation relative to the state in which it was prior to that move" [9]. A linkograph is then constructed by linking related moves.

She states that the links are established by discerning, using domain knowledge and common sense, whether a move is connected to the previous moves.

Using the FBS coding scheme design processes are an automatic consequence of the generation of a linkograph as the two ends of a link have an FBS issue and the transition between those issues defines a design process. The 8 design processes in Figure 1 map onto the start and end issues of a link in the linkograph, Table 6.

**Table 6**. FBS Processes

| Design Process | Link |
|---|---|
| Formulation | F>Be |
| Synthesis | Be>S |
| Analysis | S>Bs |
| Documentation | S>D |
| Evaluation | Be<>Bs |
| Reformulation I | S>S |
| Reformulation II | S>Be |
| Reformulation II | S>F |

Figure 12 shows a linkograph connecting the design issues. Column 1 in this study is the participant, column 2 is the segment number and column 3 is the design issue of the protocol. The dots represent the segments and the links and the gray arrow lines represent the derived design processes. The four links represent four design processes.

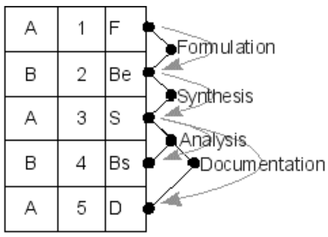


**Fig. 12** Exemplar case showing the production of the design processes from the construction of the linkograph.

Segment 3 has two links, which indicate it spawns two processes: analysis (S > Bs) and documentation (S > D). Considering the participant who responded as the one who contributed to that design process, the link from segment 1 to segment 2 is a formulation process by participant B.

## Team Design Processes

Figure 13 shows the means (average of the individuals) and the standard deviations of the design processes of the team over the entire design session.

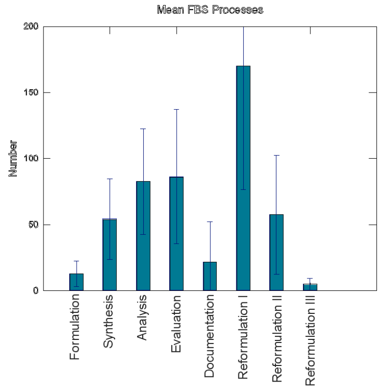


**Fig. 13** The means and standard deviations of the distributions of design processes of the whole team.

In order to compare if there are changes of the design processes the first, middle, and last 300 segments of the protocol were extracted and the total number of FBS processes in each group were counted, Figure 14.

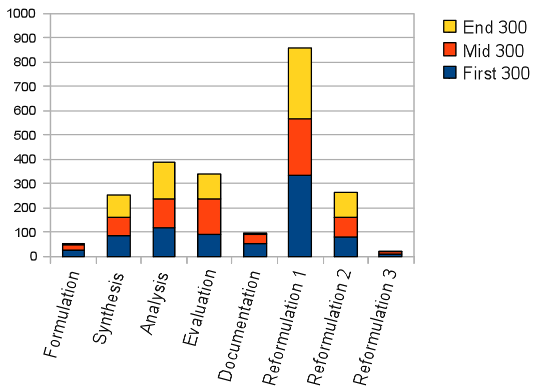


**Fig. 14** The distribution of design processes counting 300 segments from the beginning, middle and end of the session.

There is no formulation and reformulation type III at the end of the session which is in agreement with Asimow's model.

**Comparing Design Process Distributions**

Figure 15 shows and compares Allan's design processes over the three periods with those of Tommy and Todd.

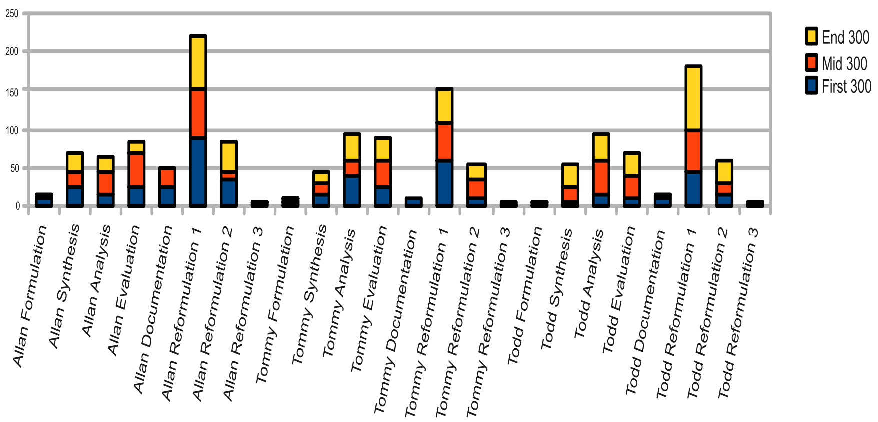


**Fig. 15** The distribution of design processes of Allan, Tommy and Todd, measuring the first, middle and last 300 segments of the session.

Table 7 shows the results of the paired-t test to determine if the distributions of individual's design processes change significantly over the course of the session.

**Table 7.** Probabilities of paired-t test of individual's design processes count

| | First and Middle | Middle and Last | First and Last |
|---|---|---|---|
| Allan paired-T | 0.78 | 0.42 | 0.10 |
| Jack paired-T | 0.61 | 0.95 | 0.62 |
| Chad paired-T | 0.05 | 0.11 | 0.36 |
| Tommy paired-T | 0.75 | 0.89 | 0.76 |
| Todd paired-T | 0.09 | 0.18 | 0.03 |
| Sandra paired-T | 0.27 | N/A | N/A |
| Rodney paired-T | 0.36 | 0.73 | 0.40 |

These results suggest that Chad's distribution of design processes changes from the start to the middle of the session. Within the first 300 segments, Chad's idea of "... a hot ball like a ball point pen" had not been considered by the group and received a very negative response by Todd “we've done that, we did that”. Following that Chad's design processes contribution drop significantly, Figure 16. Further, they indicate that Todd's starting and ending distributions of design processes were different.

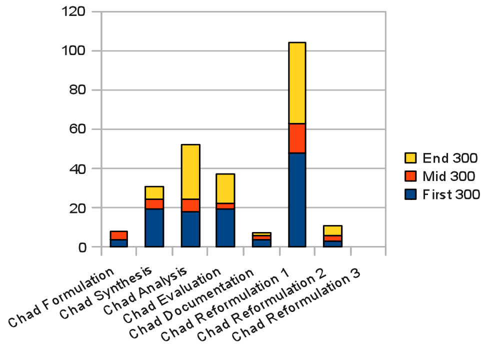


**Fig. 16** Chad’s change of distribution of design processes during the session.

### Interactions Between Team Members Measured Through Processes

The data in the linkograph allows for an examination of processes at a finer level of granularity. It is possible to examine the interactions between team members during design processes since each link in the linkograph has an individual at both ends. Each individual’s processes can be measured using this information. Figures 17 and 18 show all the design processes of three members of the team: Allan and Tommy. The distribution of the processes is again in three groupings: the first 300, the middle 300 and the last 300 segments of the protocol. The label of the horizontal axis shows the people at the two ends of the link separated by “>”. For example in Figure 17, in the subgraph titled Allan’s Formulation, “Jack>Allan” means Jack raised an F issue and at some time later Allan responded to Jack with a Be issue. This indicates that the process “formulation” took place. Similarly in the subgraph of Figure 17 titled Allan’s Reformulation I, “Todd>Allan” means Todd raised an S issue and some time later Allan responded with an S issue. This indicates that the process “reformulation I” took place. In both cases the processes were carried out by Allan.

A qualitative analysis of Figure 17 indicates that the sources of the issues of Allan’s processes were primarily himself, irrespective of the process involved, with the exception of Reformulation I. In Reformulation I the interactions with issues raised by others outweighed Allan’s interactions with his earlier issues. Further, it can be seen that in Reformulation I Allan's behavior changed from beginning to middle to end. It would be interesting to see the mean transit times for Allan. However, this is left for later analysis.

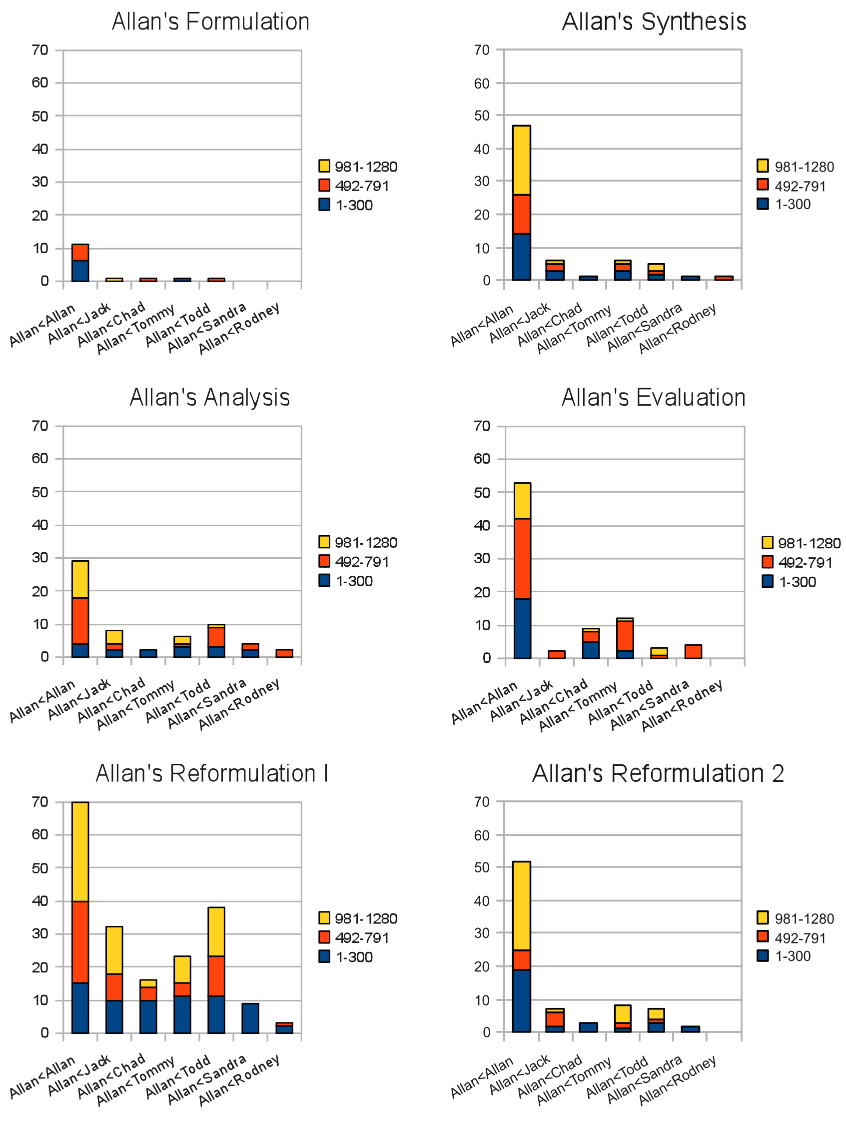


**Fig. 17** The processes and their team member sources between Allan and other members of the team.

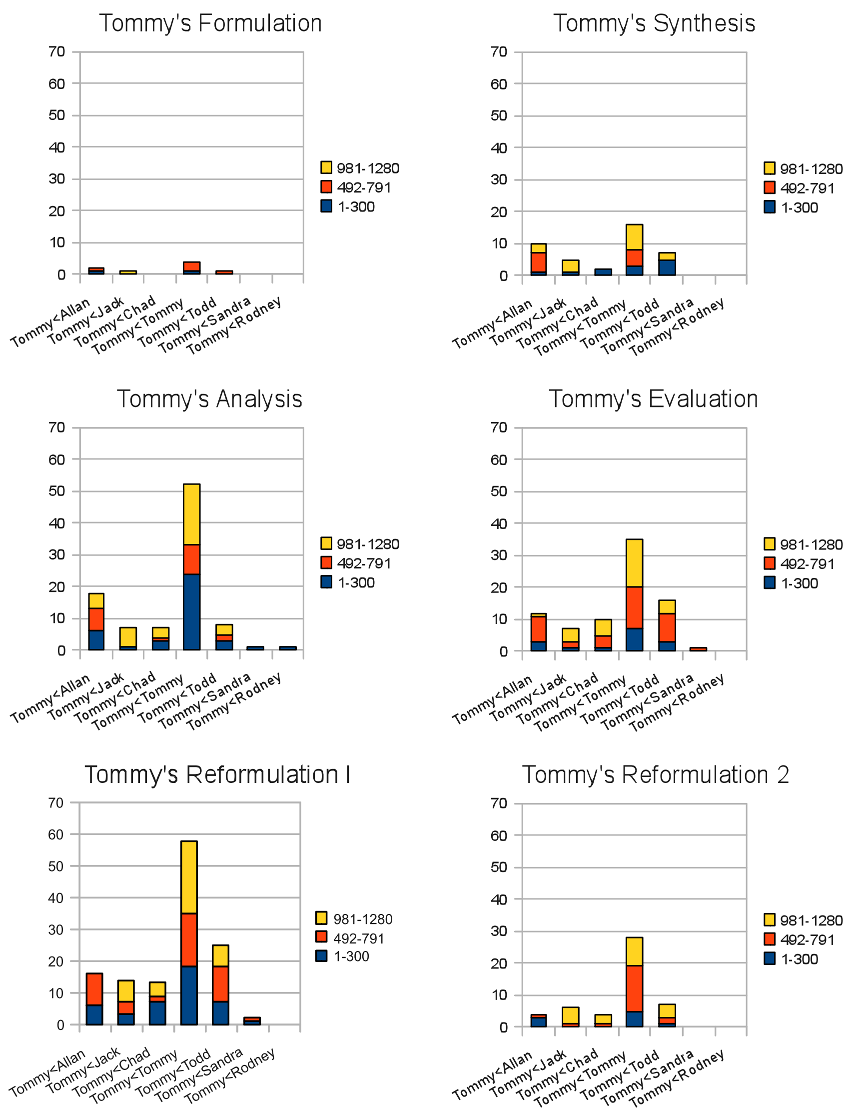


**Fig. 18** The processes and their team member sources between Tommy and other members of the team

Tommy's process behavior was similar to Allan's in that he developed processes linked to issues that primarily he brought up. However, unlike Allan the distribution of sources of issues that are the bases of his processes are more varied.

These results indicating that self is a primary source of design processes is surprising as many believe that brainstorming or group process is one of the important sources for ideas. Minneman [10] even argued that design work emerges from the interactions of the group to establish, maintain, and develop a shared understanding. He suggested that designs are created through an interactive social process. However, in the study of communication and decision making, Hewes [11], based on socio-egocentric theory, claimed that the content of social interaction in small groups does not affect group outcomes; rather those non-interactive *inputs* factors are more important. The *inputs* are:

> "*shared variables that individual group members bring to a discussion, such as cognitive abilities and limitations, knowledge of the problem or how to solve problems individually or in a group, personality characteristics, motivations both individual and shared, economic resources, and power*" (Hewes, [12] p181).

The basis of Hewes' claim was from a cognitive resources point of view – when the task is difficult, individuals in the group will compromise social tasks in order to reduce cognitive load and increase efficiency in reasoning by egocentric or private speech.

**Changes in Interaction During Design Session**

In these results the changes that take place over the course of the design session as members of the team interact with each other can be observed and quantified.

Take as an example Tommy's interactions with other members of the team over the three periods presented in Figure 18. In the first 300 segments Tommy's analysis processes were primarily related to issues that he raised. However during the middle 300 segments almost half were raised by other members of the team. In the last 300 segments again almost half of his analysis processes were related to issues raised by other team members.

Tommy's evaluation process behavior changed from the middle 300 segments to the last 300 segments. In the middle 300 segments he interacted, in terms of issues raised, more with other members of the team than in the last 300 segments. The opposite behavior can be observed in Tommy's reformulation II processes. The behavior of each individual varied over the design session.

This range of different behaviors by individual team members changing during the design session implies a change in team behavior.

## Conclusion

This paper has presented a course-grained set of results and then a fine-grained set of results derived from an ontologically-based coding scheme applied to a protocol of a team of designers in industry brainstorming.

Word counts and turntaking are one course-grained representation of the behavior of the team and its members. The results from word counts and turntaking showed that their interactions increased but their number of words remained fairly constant. This may indicate they have learned by producing a shared mental model, which is implied by the increased interaction with each interaction requiring fewer words to communicate.

The use of an ontologically-based coding scheme produced a number of increasingly fine-grained representations of the behavior of the team and its members based on issues and processes. The technique was able to isolate the issues and a statistical distribution of the team and its individual members in terms of issues was presented.

From a linkograph of the session, coupled with the issues at the segments at each end of a link, the design processes were derived. Formulation and reformulations dominated the session for the team and for the individuals in the team.

The design processes could be further articulated by examining not just the issues at each end of a link but also the individuals attached to those issues. This provided a very fine-grained representation of the process behavior of individuals by connecting them to each individual who raised the issue from which the process was generated. With this data it is possible to examine and measure the changes in behavior of individual team members and of the team as a whole across the design session.

## Acknowledgements

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