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TIME VARIATION OF DESIGN "STORY TELLING" IN ENGINEERING DESIGN TEAMS

Shuang Song, Andy Dong, and Alice M Agogino

Abstract

Engineering design practice can be viewed as a process of "story telling," where the "stories" generated explore various aspects of the design process and the designed artefact. This paper focuses on the study of the design process by using computational linguistics to analyze time variant patterns of "story telling" in eight multidisciplinary student design teams at the University of California at Berkeley, USA. We examine the oral and written histories left by the designers through their documentation, presentation material, and e-mail communication. A formal, quantitative methodology for time variant analysis of "story telling" in engineering design teams based on metrics of semantic coherence is established. Results from the analysis suggest a positive correlation between design outcomes and patterns of the average semantic coherence over time as well as with variation in semantic coherence between design stages. This research provides empirical evidence of the phenomena of changing levels of coherence in "story telling" in design and the scope of design concepts explored by design teams. Further, we show that both the e-mail data set and the documentation data sets contain approximately the same amount of "story telling" capacity.

Keywords: Design teams, product design lifecycle, latent semantic analysis, coherence

1 Introduction

Engineering design is a complex technical pursuit mediated by social processes such as communication, negotiation, and shared agreements. Given the complex orchestration of craft, human cognition, and social dynamics, a wide range of perspectives, including technical problem-solving, social networks, and theory/philosophy, is important for studying designing.

In this paper, we regard engineering design practice as being connected by a "story telling" process. We define "story telling" in design as establishing a coherent story about the design process and the designed artefact by bringing coherence to the perspectives and interests of each design team member. "Story telling" fixes the dialog of pluralistic contributions by those involved in the design process into the single designed artefact, to bring "harmony to the underlying object world" as Bucciarelli [1] wrote. The "stories" generated explore various facets of the design process and the designed artefact. They convey the value the product will bring to the people who will use it. They capture the real-world context in which the design concepts evolve in the product design lifecycle. They reflect the conflicting interests and resulting reconciliation and shared agreements of the design team members. Buchanan theorizes that design involves a "skilful practice of rhetoric … through all of the activities of verbal invention and persuasion that go on between designers, managers and so forth, but also in persuasively presenting and declaring that thought in products." (p. 109) [2] Studying engineering design from the viewpoint of "story telling" frames design in an emergent perspective to understand how collective properties of design – technical problem solving, social networks, information processing – contribute to a narrative of the design process and designed artefact.

The research reported in this paper focuses on the study of the design process by analyzing time variant patterns of “story telling” in engineering design teams using computational linguistics. Although we acknowledge the integral nature of the design sketches and drawings to the “story telling”, this research only examines the written and oral histories left by the designers through their documentation, including reflections on the design process, presentation documents, and electronically-mediated communication via e-mail. “Story telling,” as a mechanism for studying the social experiences in design, has also been successfully applied in ethnographic studies of design teams. [3] A “story telling” archival system such as that described by Garcia [4], employing multimedia and a moviemaking metaphor to capture the description of the design, could enrich the textual explanation of the design. Three research issues are discussed in relation to examining the time variant patterns of “story telling”. First, based on our definition of design “story telling”, how can we identify, represent, and visualize “story telling” of engineering design teams? Second, how does the “story telling” evolve over time? And finally, are there any correlations between patterns in design “story telling” and the outcome of the team? That is, what insights into the design process will quantitatively depicting patterns in “story telling” provide?

By applying the computational text analysis technique of latent semantic analysis (LSA) to the design corpus of engineering design teams, we were able to measure and visualize the time variation of design “story telling” of each team. In order to compare the “story telling” capacity of design documents and e-mail, we studied the coherence of “story telling” identified from design documents and the e-mail separately. We also measured the amount of communication for each team, including the volume of messages, the frequency of messages for each of the product design stages, and individual team members to compare how the amount of communication might have affected “story telling.”

Our conjecture is that the variations in semantic coherence of design stories offer a picture of the progression of the design process, of the iterative broadening and narrowing of “searching” for design solutions. We hypothesize that the coherence of design “story telling” will vary over time. This variation may reflect changes in shared agreements of the design team, the breadth of design concepts explored, and levels of shared understanding. Nonetheless, teams able to synthesize a coherent story at the conclusion of the design process will likely have better design outcomes. This is consistent with the results of our prior research, which showed that teams with high levels of shared understanding generally perform better in terms of the quality of the design outcomes [5]. One unexplored aspect of this prior research was an investigation into the patterns of “shared understanding” and coherence of “story telling” over the design process. In particular, these previous results prompted us to ask whether teams that exhibit “group think,” that is, teams with low semantic variation in “story telling” over time, will likely have poorer design outcomes than teams with reasonable levels of variation. The research herein develops a methodology for mapping the alternative visions of teams of designers, in which the narratives and plots construct connections and associations for a contextual portraiture of the design process over time.

2 Methodology

A multidisciplinary graduate design course at the University of California, Berkeley provided the test bed for this study. In this course, graduate student teams of four to six students from engineering, information science, business, and industrial design conceive, synthesize and prototype engineered products. They work together as a unit in self-selected and self-managed teams, with coaching from faculty and industry consultants. This design course provided us with important resources about the product design process. As in industry, the teams had authentic deadlines and deliverables for each design stage. The design process proceeded from ideation to concept generation, detailed design, financial analysis, and a working prototype in a four-month period. The documentation produced by each student in the teams captured not only the details about the product but also their own personal reflections on the design process and their own perspective of the meaning of the product. From each of these individual and group perspectives, we measured the synthesis of a coherent "story."

We captured design documentation (such as mission statements, customer feedback, product testing and engineering memos, presentation materials, and individual and team reflections on the design process and the product) and e-mails from these student teams. We applied established computational linguistic techniques for analyzing full-text documentation. We represented the teams' design corpus (all design documents and e-mail communication) through a vector model. The text analysis method we adopted in this research is called latent semantic analysis (LSA) [6]. LSA is a computational text analysis technique that takes advantage of implicit higher-order structure in the association of terms within documents to detect semantic similarities. The application of LSA to analyzing design documentation is based on our prior research in applying computational text analysis to study design cognition [5][7] and related research in measuring text coherence [8][9]. We refer the reader to these resources for the detailed descriptions and underlying mathematics of LSA.

LSA was performed over a matrix comprised of all the documents for each team. The rank of the matrix is the total number of documents. Based on our preliminary analyses, we found that good predictions were obtained by using the top third of the total LSA dimensions, which correspond to the rank of the matrix. Then, the documents or e-mail were sequenced consecutively in time and divided into the separate phases of the design process according to Cooper's Stage-Gate [10] process model: 1) preliminary investigation; 2) detailed investigation; 3) development; 4) testing and validation; and 5) launch. The Pahl and Beitz [11] engineering process model is similar and is interchangeable. Because the students do not launch the product, only the first four phases were considered. Based on the sequence, the coherence between two consecutive documents and the average coherence during the design stage were computed. Finally, the semantic coherence variation in "story telling" over these stages was calculated.

Several established techniques exist to measure semantic coherence using LSA. The coherence measurements applied in our previous research [12] adopted a document clustering measurement, which is appropriate for measuring the coherence of many documents simultaneously. In this paper, however, the interest is in measuring the pair-wise coherence of documents consecutive in time to detect the change in coherence over discrete periods of time. As LSA provides a fully automatic method for comparing units of textual information to each other in order to determine their semantic relatedness, the coherence used in this paper is measured by comparing the vectors for two design documents in a k-dimensional LSA space. This measurement is taken from a previous study by Foltz [9], which measures the similarity of two documents using a "cosine" measurement. Because the documents are represented as vectors in a k-dimensional LSA space, one can measure the angle between them using Eq. 1.

$$\cos(\mathbf{d}_i, \mathbf{d}_j) = \frac{\mathbf{d}_i \cdot \mathbf{d}_j}{\|\mathbf{d}_i\| \|\mathbf{d}_j\|} \quad (1)$$

where $\mathbf{d}_i$ and $\mathbf{d}_j$ are singular vectors representing the i^{th} and j^{th} document produced by a design team and for which the time sequence of the documents is such that $t_i < t_j < t_{i+1} < t_{j+1}$. The "closer" the vectors are, the higher the value of the cosine with a maximum value of 1 (perfectly similar) and a minimum value of –1 (exact opposites). A value of 0 means no similarity but not necessarily diametrically opposed either.

To study variation of semantic coherence within and between design stages, we classify coherence into two types. The first one is called *intra-stage semantic coherence* discussed in Sections 3.1 and 3.2. The second is called *cross-stage semantic coherence* as discussed in Section 3.3. The *intra-stage semantic coherence* is calculated as the average of the coherences of documents pair-wise consecutive in time within a design stage (i.e., the "d" variables in Eq.1 represent the individual documents in each stage). The *cross-stage semantic coherence* is computed as the cosine measure between the centroid document vectors, which is defined as the arithmetic average of the entire document vectors, for each adjacent design stage. Here, the variables in Eq. 1 are the centroids of the documents in each stage as calculated by Hill [5].

3 Results

3.1 Time Variation in Semantic Coherence

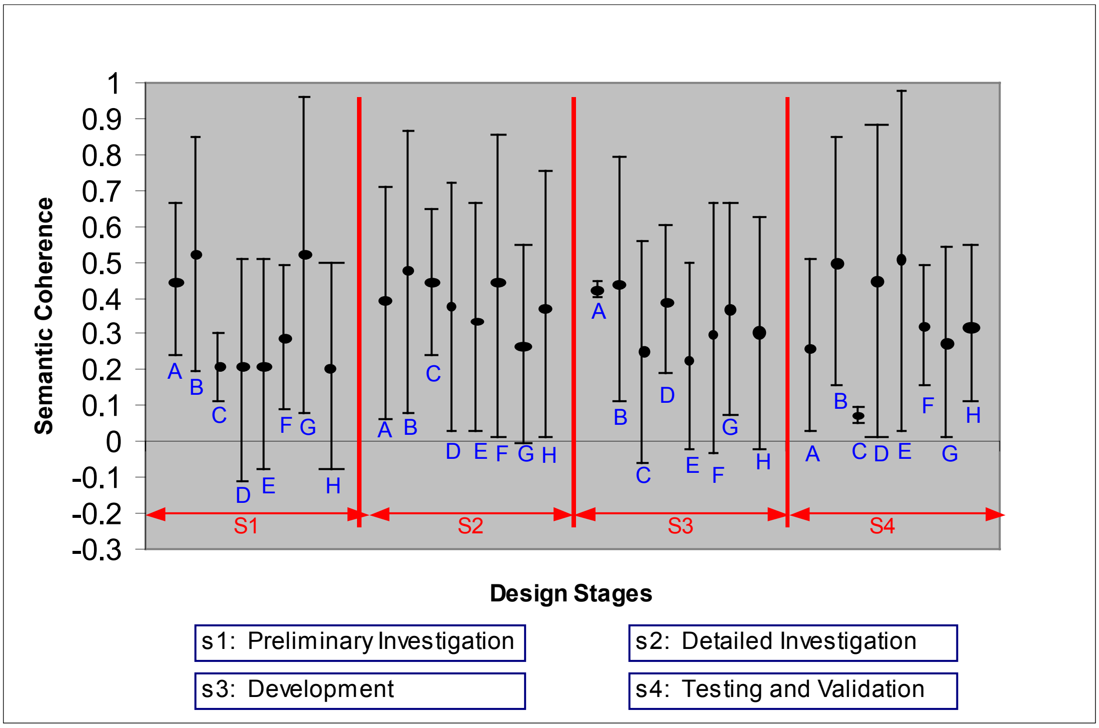

Figure 1 Variation of average semantic coherence within each design stage

Figure 1 illustrates a picture of the variation of semantic coherence of all design teams in the study throughout the design stages. There were a total of eight design teams identified as A to H. Each bar represents the variation of semantic coherence of a design team in a certain design stage, with a middle point indicating the average coherence for that stage (intra-stage semantic coherence). Three patterns appear to emerge.

1. Low to high: Teams D, E, and F started with relatively low average semantic coherence, but after some cycles of variations, they ended up with high semantic coherences during the final stage of design.
2. High to low: Teams A, C, G, deteriorated to a lower semantic coherence than their start points.
3. No change: Team B and H exhibited little change in average semantic coherence between the start point and the end point. However, Team B maintained high semantic coherence throughout while Team H struggled to create a coherent story, as evidenced by their low semantic coherence.

At the beginning of the design process (i.e., preliminary investigation stage), there is a wide variation of semantic coherence (e.g., large error bars in Figure 1), but that variation diminishes towards the end. This pattern seems to confirm the notion that the design process is characterized by an iterative broadening and narrowing of design possibilities, and an iterative reconciliation of design interests and conflicts towards a set of shared agreements.

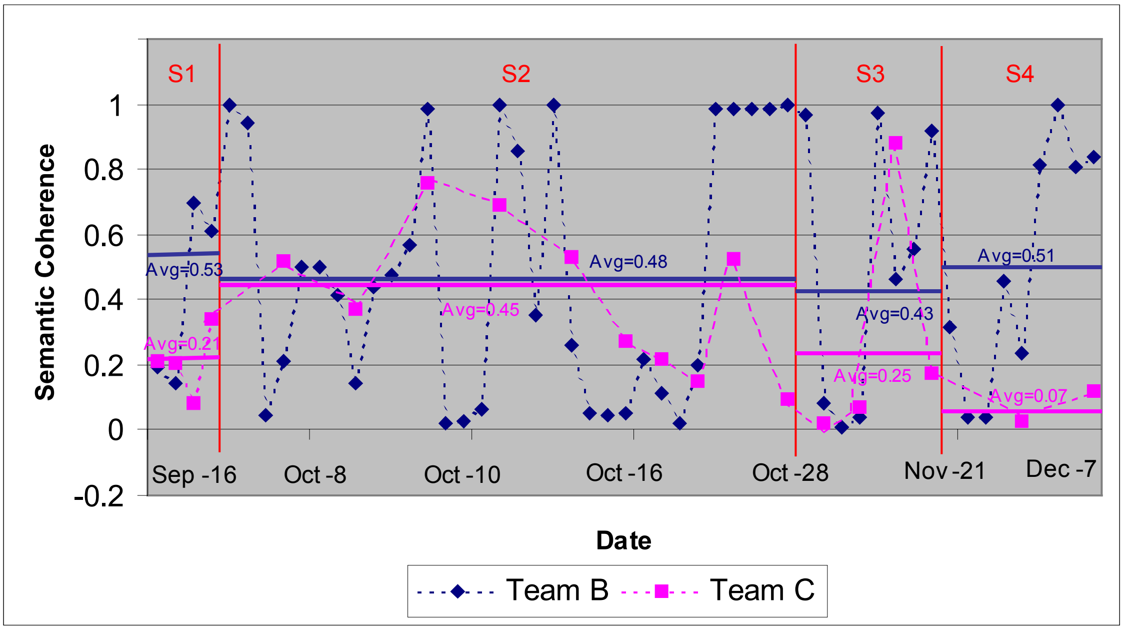

Figure 2 Variation of semantic coherence of Team B and Team C

Different patterns emerge as we view the semantic coherence for each document pair over the design process. Figure 2 shows the variation of semantic coherence of two representative design teams over the design stages – Teams B and C. Team B maintains a high level of average semantic coherence over time, but with high levels of cyclic variation within each stage. Each point represents the semantic coherence between two consecutive documents. Dotted lines between points are only for visualization purpose. Thick lines indicate the average coherence (arithmetic average) for each stage. In spite of this cyclic variation, Team B seems to end each stage at a relatively high level. As shown in Section 3.3, this coherence or ability to communicate a "shared vision" at the end of each stage is reflected in the high mark given by the faculty at the end of the class. Team C, on the other hand, shows less cyclic variation in coherence, yet seems to end each stage at a relatively low point. Although the team started out low, it managed to pull up their average coherence during stage two, but eventually ended up with a diverged "story" at the end. As discussed further in Section 3.3, this is reflected in their poor faculty mark for their project.

The occurrence of increasing coherence with cycles of divergence during the design process is always desirable, with iterative broadening and narrowing of the design possibilities, and an iterative reconciliation of design interests and conflicts towards a set of shared agreements. In contrast, the situation of decreasing coherence in design "story telling" is likely disruptive and increasingly dysfunctional. Such patterns may require intervention to promote focused design behaviour and thinking. Design teams, whether self-managing or otherwise, should monitor the variation in their design thinking, as manifested through "story telling" to determine whether their behaviour accords with the demands of the design situation.

3.2 Patterns of E-mail Usage

We observed more frequent email communication during the early stages of product design than in the latter stages, as shown in Figure 3. The figure illustrates six groups' intra-group e-mail communication in terms of volume and frequency respectively during their semester long product development process. (Note: Two members of Team A and Team D opted out of the e-mail study; thus, their results are not available.) The content of e-mail messages are related only to the product and the design process. We have filtered out all the irrelevant messages, such as scheduling meeting times, which is very common in the e-mail communication among design teams. We postulate that this change in frequency indicates that early on, the teams were actively establishing a set of broad shared agreements on the design and the design process, in essence a team mental model. However, once this process was "completed," they focused on specific design and engineering tasks associated with the synthesis of the product.

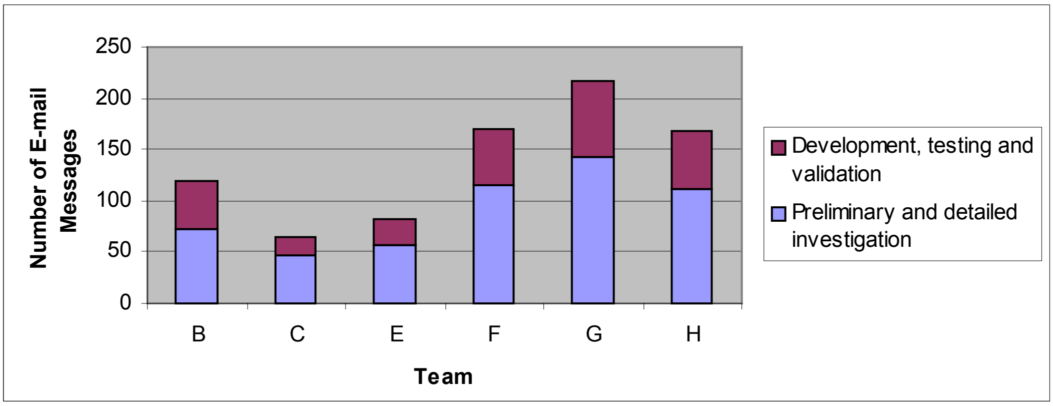

Figure 3 Comparison of volume of e-mail messages between earlier and latter design stages

Second, from the comparison study of analyzing the design documents and e-mail messages separately, we found that the semantic coherence of "story telling" from these two sources follow approximately the same pattern over time, as shown in Figure 4. Note that both design documents and e-mails were created on discrete days. For visualization purposes, we display the fitted curves to highlight the trends. The figure suggests that communication records provide the same context of design "story telling" as the design documents. However, it is difficult to ascertain the individual contribution of each team member from design documents because these documents tended to be group-authored. Future studies will compare individual variations in design "story telling" to the team's "story telling."

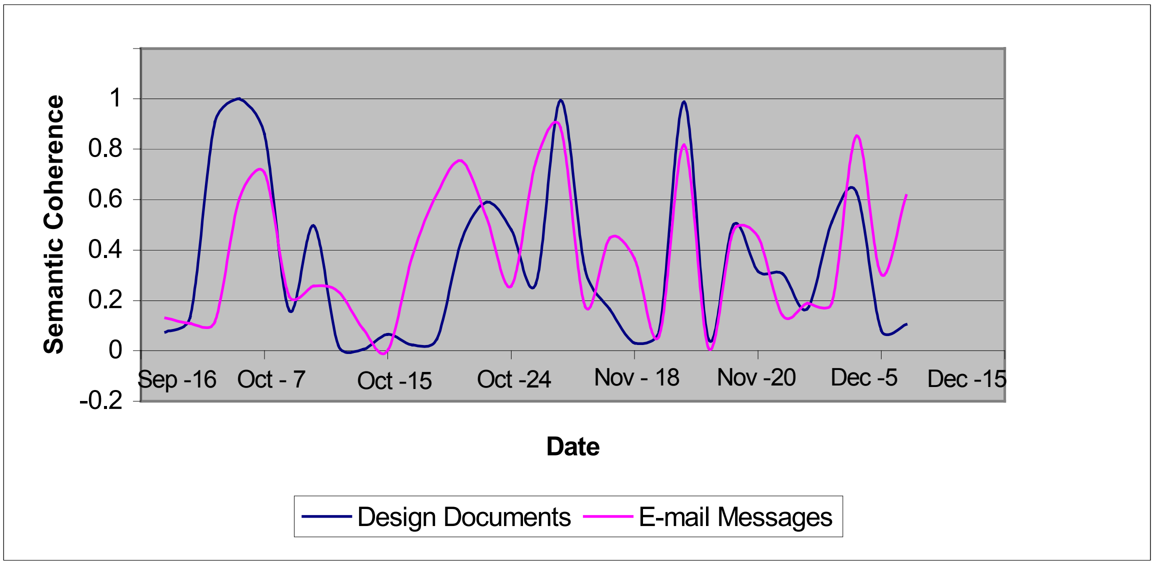

Figure 4 Time variation of semantic coherence from design documents and e-mail messages of Team G

3.3 Comparison of Patterns of Semantic Coherence to Design Performance

In a prior study [5], we found that *overall* semantic coherence is correlated with design outcomes. In the study herein, we analysed the data to test whether *patterns of semantic coherence variation over time* is also correlated to design performance. Intuitively, one would expect that a well-performing team might start with low coherence in the formative stages of the design process, cycling through divergent-convergent phases during the design. However, the coherence of the story should increase towards the final stages. Poorly performing teams might start and end with low coherence. Other seemingly promising teams, might even start with high coherence, degenerate, and end up with low coherence or not vary much at all in coherence – possibly a signature of "groupthink" or inadequate exploration of the design space.

Table 1 Correlation between cross-stage semantic coherence variation and design outcomes

	Faculty Rank	Semantic Coherence Variations Between Design Stages		
		S1 & S2	S2 & S3	S3 & S4
Team A	8	0.48	0.21	0.20
Team B	1	0.39	0.04	0.54
Team C	6	0.56	0.35	0.32
Team D	5	0.36	0.05	0.30
Team E	2	0.27	0.18	0.67
Team F	3	0.04	0.27	0.64
Team G	4	0.26	0.32	0.05
Team H	7	0.23	0.54	0.36

To compare the semantic coherence variation in "story telling" over time to team performance, we examined both intra-stage and cross-stage variations. Figure 1 (from section 3.1) shows the variations of the intra-stage semantic coherence of all design teams. Table 1 shows the faculty ranks for each team, along with the cross-stage semantic coherence. The Faculty Rank is the ordinal grade that the faculty placed on the team based on a review of the team's performance throughout the process, the quality of the final product and input on the final product from a team of industrial reviewers. A rank of 1 would mean that the team scored the highest. The last three columns report the cosine value; the lower the cosine value, the larger the relative semantic changes. Note S1 through S4 are labels for the four design stages we defined in Section 3.1.

While not statistically significant, patterns of cross-stage semantic coherence over time appear to be linked with successful design outcomes. Figure 5 depicts the variation of cross-stage semantic coherence reported in Table 1. We can visualize different patterns of changing semantic coherence for each design team. Teams with large variations of semantic coherence, especially in earlier stages, such as Team E and Team F, had better design outcomes than teams with lower levels of variation that nonetheless produced a coherent story at the end, such as Team H; or teams that semantically diverge, such as Team C. Highly ranked teams B, E, and F all increased their semantic coherence. Low performing teams A, C, and G actually decreased their coherence. Team D performed relatively well although did not appear to "pull out" of their low coherence during the mid-stages of design.

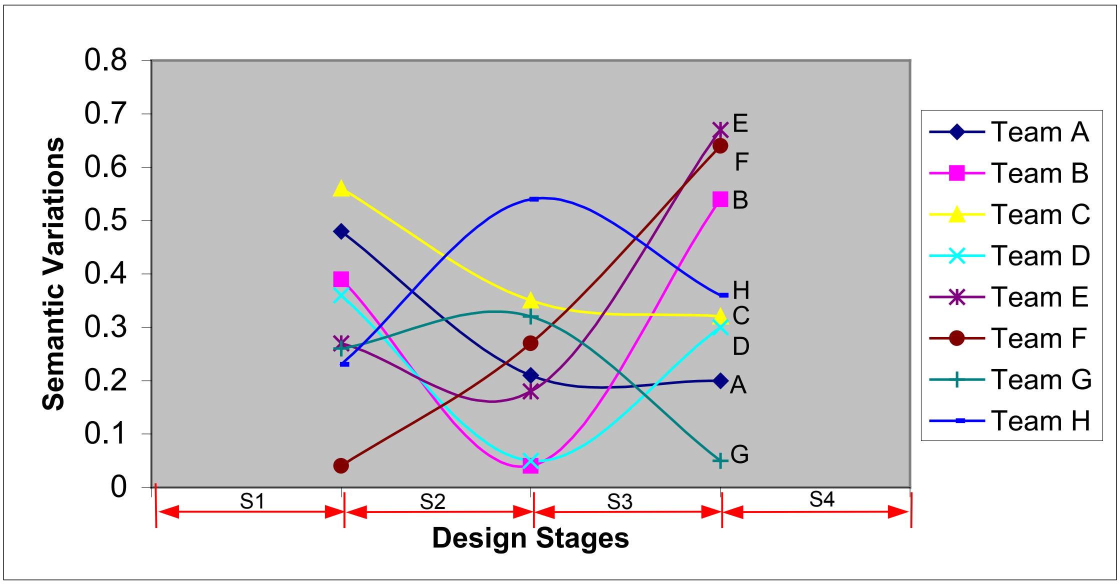

Figure 5 Semantic coherence variations between design stages

3.4 No Correlation between E-mail Volume and Frequency to Performance

Our data show that there is no apparent correlation between the total number of e-mail messages and design outcomes. While the volume and frequency of e-mail may change over the design process, these variables do not appear to relate to better performance. That is, higher levels of email communication do not necessarily lead to better design outcomes. Communication that leads to coherent "story telling" may, however. We also observed that some members dominate e-mail communications. Figure 6 shows the distribution of e-mail communications among members in Team F. Member 2 sent out 39% of the messages to the whole group. Does this mean deeper and better involvement in design? In order to ascertain the influence of this member's dominance of semantic coherence of the design "story telling", we measured the cosine similarity between the each member's e-mail messages and all messages in a design team. Figure 7 indicates messages from Member 2 do have a slight higher coherence to the design "story telling" than messages from most of the other team members. The impact of the individual on group communication will be studied more thoroughly in future research by triangulating with other tools, such those associated with social network theory.

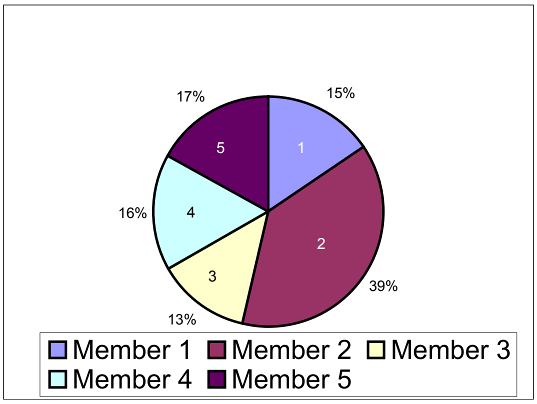

Figure 6 E-mail distribution of Team F

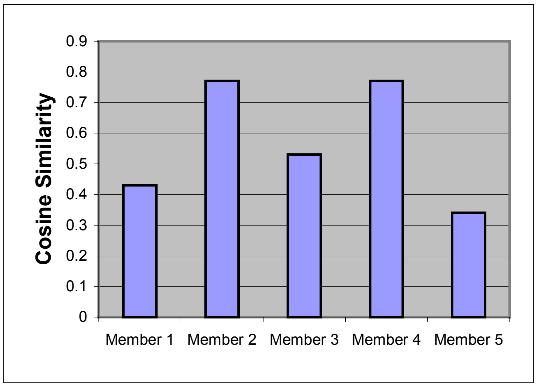

Figure 7 E-mail semantic coherence between each member and all for Team F

4 Conclusions

This paper describes a formal, quantitative methodology for time variant analysis of "story telling" in engineering design teams based on the metric of semantic coherence. The methodology includes analyzing a design team's corpus using latent semantic analysis, computing the pair-wise document semantic coherence over time, the average semantic coherence within each design stage, and the variation in semantic coherence across the design stages. Additionally, examining the team's e-mails indicated that both sets of data sets about the design contain approximately the same amount of "story telling" capacity. While some open issues remain as to the interpretation of the patterns of variation, this paper provides empirical evidence of the phenomena of changing levels of coherence in "story telling" in design and the scope of design concepts explored by design teams. The research also raises possible hypotheses that associate these patterns of semantic coherence in design "story telling" to the following other aspects of the design process:

1. <u>Technical Problem Solving</u>: The changing patterns of "story telling" point to the iterative broadening/narrowing nature of engineering design. In the early conceptual design stages, it is advantageous for the design team to explore broadly potential design solutions as illustrated by the broad variation in coherence. Towards the end, however, teams should resolve conflicting ideas to converge on an agreed-upon product direction.
2. <u>Social Networks</u>: The semantic coherence is an indicator of the level of shared understanding or shared vision of the team of the function, structure and behaviour of the designed product. Design teams articulate through text the design's function, structure and behaviour. Their documentation seems to share latent semantics that tell a coherent "story" of the evolution of the design.
3. <u>Theory/Philosophy</u>: Design is teleogical. The selection of materials, functions, and manufacturing processes, and decisions about size, shape, colour and finishes are not incidental. Rather, they point to a controlled expression of the product's meaning and function that the designers intend to communicate to the end-user.

This paper establishes a formal methodology for providing a real-time window into the design process and coherence of design thinking of the design teams. At this time, it is too early to state that absolutes exist in semantic coherence nor can we recommend ideal levels for each design stage. Rather, the methodology should be considered as means for contextualizing portraiture of design in terms of unique teams and situated design contexts. Design teams could also apply the method to reflect on their own performance with the ability to address important process questions. *Are we too focused when we should be expanding our scope? Have we been diverging for too long?* Our goal is to eventually sort the metrics of local performance of design teams to global metrics of performance.

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Alice Agogino, Roscoe and Elizabeth Hughes Professor of Mechanical Engineering
Department of Mechanical Engineering, University of California, Berkeley
5136 Etcheverry Hall, Berkeley, USA
Tel.+1-510-642-6450; Fax.+1510-643-5599; E-mail: aagogino@me.berkeley.edu;
URL: http://www.me.berkeley.edu/faculty/aagogino/.