INTERNATIONAL DESIGN CONFERENCE – DESIGN 2020
https://doi.org/10.1017/dsd.2020.294

SEMANTIC ANALYSIS OF ENGINEERING DESIGN CONVERSATIONS

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Abstract

To objectively and quantitatively study transcribed protocols of design conversations, we apply a semantic analysis approach based on dynamic semantic networks of nouns. We examined the applicability of the approach focused on a dynamic evaluation of the design problem solving process in engineering design educational settings. Using a case of real-world case, we show that the approach is able to determine the time dynamics of semantic factors such as level of abstraction, polysemy, information content, and quantify convergence/divergence in engineering design conversations.

Keywords: design cognition, design process, human behaviour, semantic analysis, enginnering design conversations

1. Introduction

Verbal reports provide a powerful source for studying problem solving in design. However, identifying useful data about the cognitive processes underlying human problem solving and creativity from transcribed protocols of design conversations is a challenging task. This is due to the fact that not all aspects of human creative skills are verbalized or represented at a consciously accessible level (Boden, 2004). Semantic networks address this problem by furnishing a structured representation of not only those concepts that are explicitly verbalized in the conversations (Georgiev et al., 2008, 2010; Taura and Nagai, 2013), but also of the inexplicitly envisaged 'virtual' concepts that connect the verbalized concepts in a standardized lexical database (Yamamoto et al., 2009). The importance of the virtual concepts in the database is that they provide graph-theoretic connections between the verbalized concepts for the calculation of semantic measures. Moreover, without the virtual concepts acting as linking hubs between envisioned concepts in the designer's mind, the verbalized concepts would stay disconnected and the assessment of similarity or dissimilarity between different concepts by the human mind would remain an intractable problem. In order to attain a high degree of confidence in the accuracy of the extracted virtual concepts, the theoretical rule for their extraction needs to be based on a characteristic feature of the working human mind such as its functional reliance on the is-a hierarchy of nouns, which comprises common knowledge shared between native speakers of a given language.

Previous study of design student's performance has shown that lengthy noun phrases, formed as noun agglomerations that break grammatical rules, are important for expressing creative ideas in early phases of the mechanical design process (Mabogunje and Leifer, 1997). The number of such noun phrases in written project reports spanning three academic quarters steadily increased in time as the projects matured, and the higher number of noun phrases significantly correlated with higher grades received by the students. This shows that the agglomeration of nouns is instrumental in designer's attempt to express the inexpressible and to transform vague ideas to physical reality (Mabogunje and Leifer, 1997).

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In the approach presented here, we use WordNet 3.1 as a lexical database for the construction of semantic networks containing only nouns. The constraint to work only with the lexical category of nouns is necessitated by the sparsity of structural cross-subnet pointers between the four subnets of WordNet for nouns, verbs, adjectives or adverbs (Fellbaum, 1998). Because nouns form the largest and deepest hierarchical taxonomy in WordNet, the pairwise similarity of nouns could be evaluated at a much finer resolution compared to verbs, adjectives or adverbs. The efficacy of semantic networks of nouns for computational reconstruction of difficult-to-observe processes in design-thinking and exploration of creativity in conceptual design was demonstrated in previous studies using different sets of experimental data (Georgiev et al., 2008; Yamamoto et al., 2009; Taura et al., 2012; Georgiev and Georgiev, 2018; Nomaguchi et al., 2019). Semantic network-based approaches help further refine understanding and develop theories on creative problem solving processes (Nomaguchi et al., 2019; Olteţeanu et al., 2019).

Studying the temporal characteristics of the design process using traditional protocol analysis coding schemes and linkography has been beneficial for obtaining insights into the generation of creative ideas and solutions. Linkography is a method for analysis of decisions and activities that occur in the process of design thinking (Goldschmidt, 2014). Linkography is performed by trained design experts who parse the design conversations into elementary steps called design moves, which are then connected through backlinks to previous moves or forelinks to future moves. Once the linkographs are created, they could be evaluated using an information theoretic approach (Kan and Gero, 2017). The drawbacks of linkography and other traditional methods relying on expert raters is that they suffer from known inter-rater reliability issues (Jeffries, 2017) and cannot be automated for routine use by non-experts.

To objectively and quantitatively study transcribed protocols of design conversations, here we apply a semantic analysis approach based on dynamic semantic networks of nouns. We examined the applicability of the approach focused on a dynamic evaluation of the design problem solving process in engineering design educational settings. Using a real-world case, we show that the approach provides a robust evaluation of the time dynamics of semantic factors such as level of abstraction, polysemy, information content, and quantifies convergence/divergence in engineering design conversations.

2. Semantic analysis approach

2.1. Semantic networks of nouns

Semantic networks provide a structural representation of knowledge in the form of graphs (Sowa, 1991; Hartley and Barnden, 1997). Each graph is composed of two main elements: vertices, which represent individual concepts, meanings or ideas, and edges, which represent existing relationships between different concepts, meanings or ideas. Depending on the type of relationship between the vertices in the graphs, the edges could be undirected (act like an unordered pair of vertices) or directed (act like an ordered pair of vertices) (Diestel, 2017). After agent's knowledge is exteriorized, recorded and represented in the form of a semantic network, a number of graph-theoretic measures could be employed for quantitative analysis and hypothesis testing. Here, we have studied human creativity in engineering design conversations with the use of semantic networks of nouns. The rationale behind our approach is the consciously-intended, close correspondence between designer's ideas and the words chosen by the designer for the communication of those ideas to other participants in the conversations. Among all lexical categories in conversations, nouns are the most basic, important and informative in regard to describing designer's ideas (Taura and Nagai, 2013; Georgiev and Taura, 2014). This underlies our decision to represent concepts in the semantic network with single nouns. Practical utility of nouns in creative problem solving and design has been already demonstrated in previous research. For example, the generation of ideas in creative problem solving is stimulated by noun networks (Segers et al., 2005), the display of creative thought in design is associated with the ability to draw property relations between unusual noun–noun combinations (Dong, 2009), and the creative performance is enhanced by highly dissimilar noun–noun combinations that yield emergent properties of generated ideas (Wilkenfeld and Ward, 2001). For the construction of semantic networks, noun senses were not disambiguated. The main justification for this decision is that the nouns employed in the description of creative design ideas may acquire new senses different from dictionary-defined ones (Georgiev and Georgiev, 2019). In addition, the polysemy of nouns may be

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instrumental in the association of ideas, which were not considered to be related previously (Taura and Nagai, 2013; Georgiev and Taura, 2014). Semantic networks of nouns were also highly effective in attempts to reconstruct computationally difficult-to-observe processes in design-thinking (Yamamoto et al., 2009), and in exploration of creativity in conceptual design (Georgiev et al., 2008, 2010; Taura et al., 2012; Georgiev and Georgiev, 2018).

2.2. Words, meanings and semantic measures in WordNet 3.1

To impose an objective, standardized metric on the semantic networks of nouns, we have used the is-a hierarchy (hypernym-hyponym hierarchy) between noun synsets in WordNet 3.1. Synsets, which represent meanings in WordNet 3.1, are usually provided in the form of dictionary lists with one or more synonymous words. For the computation of graph-theoretic measures, however, WordNet 3.1 needs to be rendered in the form of a directed acyclic graph containing two different kinds of vertices: word vertices or meaning vertices. The core of the graph is comprised of meaning vertices, which are labelled with numeric code, e.g. M10146463 with synset {Einstein, brain, brainiac, genius, mastermind}, M05488747 with synset {brain, encephalon}, M05619057 with synset {brain, head, mind, nous, psyche}, M05625839 with synset {brain, brainpower, learning_ability, mental_capacity, mentality, wit}, or M07668194 with synset {brain}. Here, it is important to note that the meanings are not to be identified with the corresponding list of words, but rather with what is common for all listed words. Thus, M10146463 stands for 'someone who has exceptional intellectual ability and originality', M05488747 stands for 'part of the central nervous system', M05619057 stands for 'the seat of the faculty of reason' and M05625839 stands for 'mental ability'. In rare cases, the meaning could not be guessed from the synset alone, but needs to be looked up in a sample sentence provided with the WordNet 3.1 dictionary, e.g. M07668194 stands for 'the brain of certain animals used as meat'. For efficient computation of different semantic measures, the word vertices could either subsume meaning vertices or be subsumed by meaning vertices in the WordNet 3.1 graph (Georgiev and Georgiev, 2018).

2.2.1. *Abstraction of words*

Abstraction quantifies how generalized the word is in comparison with the most concrete word instance in WordNet 3.1. The abstraction of a word x is given by the complement to unity of the shortest path distance measured in edges from the root meaning vertex to a meaning vertex subsuming the word x normalized by the vertex eccentricity of the root vertex in the core graph of meanings. Different words within a synset can have different level of abstraction. For example, the abstraction of 'brain' is 0.78, whereas the abstraction of 'encephalon' is 0.61.

2.2.2. *Polysemy of words*

Polysemous words possess two or more meanings (Ravin and Leacock, 2000). The polysemy of a word x in WordNet 3.1 is given by the number of meaning vertices that are directly adjacent to x in the graph. For example, the polysemy of 'brain' is 5, whereas the polysemy of 'encephalon' is 1.

2.2.3. *Information content of words*

The information content quantifies the bits of information that are carried by a word vertex in WordNet 3.1. The normalized information content (IC) of a word x is computed from the number of subsumed leaf meaning vertices and the maximal number of such leaves in the graph using the formula $IC(x)=1-\log|Leaves(x)|/\log|Max\_leaves|$ (Blanchard et al., 2008). For example, IC of 'brain' is 0.78, whereas IC of 'encephalon' is 1.

2.2.4. *Semantic similarity of word pairs*

The semantic similarity quantifies the alikeness of two word vertices. The semantic similarity of a word pair (x, y) is the information content of the lowest common subsumer of the two words LCS(x, y), which is a meaning vertex in the graph (Resnik, 1999). For example, LCS of 'brain' and 'encephalon' is M05488747 with synset {brain, encephalon}, and the semantic similarity is

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IC(M05488747)=1; LCS of 'brain' and 'human' is M00004475 with synset {being, organism}, and the semantic similarity is IC(M00004475)=0.13.

3. Method

3.1. Dataset

We analysed the transcripts of engineering design review conversations from one team recorded in real-world educational settings at Purdue University, West Lafayette, Indiana, in 2013, which is part of the DTRS10 dataset (Adams, 2015; Adams and Siddiqui, 2013).

The context is a semester long Mechanical Engineering senior design or "capstone" design course. Undergraduate students take this course in their final year of their program (Adams and Siddiqui, 2013). The conversations are between design students, instructors, and jurors and other stakeholders. The dataset includes Concept Design Review (CDR) and Final Design Review (FDR). During the CDR, students present early work on their final solution as a formal presentation. During the FDR, students present their final work. This is an informal presentation to the Project Manager and the Project Engineer. The presentation is conducted in one of the laboratories where students build and test their prototypes. The design course finishes with a competition where an external jury selects five teams out of ten possible teams through a poster presentation. On the following day, the top five teams give a formal presentation to the external jury (Adams and Siddiqui, 2013).

3.2. Case study

We analyse one team that was selected and reached the competition stage giving formal presentation to the external jury. That was the only team that reached that stage and is available in the DTRS10 dataset. In the present study, we analyse separately the three design sessions (CDR, FDR and Competition presentation, see Figure 1). The conversation transcript of each session is split into three equal parts for quantification of time dynamics applying the method of Georgiev and Georgiev (2018). The team is called Purdue Prop Pullers (PPP) and develops a portable electric tow bar. The device could pull a light aircraft at short distances across the ground, generally across a hangar (Figure 2).

Figure 1. The CDR (top), FDR (left down) and competition presentation (right down) conversations of PPP team

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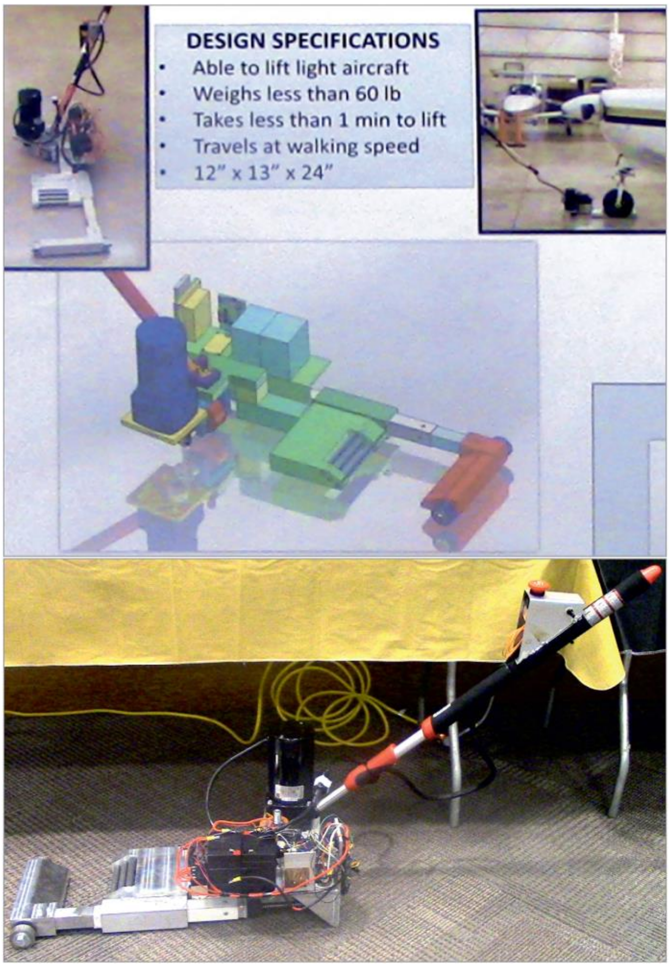

Figure 2. The developed solution by the PPP team - a portable electric tow bar that is able to lift a light aircraft

The three design sessions (CDR, FDR and Competition presentation have the following purposes (Adams, 2015; Adams and Siddiqui, 2013):

- During the CDR, students present early work on their final solution in a formal presentation.
- During the FDR, students present their final work in an informal presentation to the Project Manager and the Project Engineer (conducted in one of the laboratories where students build and test their prototypes).
- During Competition presentation, the top five teams give a formal presentation to the external jury, which selected the projects of the teams through a poster presentation on the previous day.

The following is an example of FDR conversation: *"[We] talk about, ah, any future changes that we have to make to optimize the design more. Ah, we, ah, would like to save some weight in the future, so the one of the pieces we have of solid aluminium we would cut out some area because it's not being used like for anything. Ah, we would like to use a bigger lift motor, slightly bigger…"*

3.3. Dynamics of semantic factors in engineering design conversations

To quantify the dynamics of the design problem solving conversations, we assessed the change of the four semantic factors in time. To obtain three time points for analysis of time dynamics, we divided the conversations for each session into three equal parts, denoted as T1, T2 and T3, based on word count. This division was made into whole sentences in such a way that no time point of the conversation contained less than 30 unique nouns. Regarding semantic similarity, convergence in the semantic networks was defined as an increase of the average semantic similarity in time, whereas divergence as a decrease of the average semantic similarity in time (Georgiev and Georgiev, 2018).

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4. Results

In this section, we present time dynamics of the four semantic factors of the three engineering design conversations Concept Design Review (CDR), Final Design Review (FDR), and Competition presentation in order to identify trends and compare these trends with findings from previous studies.

4.1. Concept Design Review (CDR) conversation

The dynamics of the four semantic factors for the Concept Design Review (CDR) is shown in Figure 3. The dynamics of Abstraction and Semantic Similarity for this conversation does not change much (Figure 3B and Figure 3D). Lack of dynamics of Semantic Similarity for this conversation is notable compared to previous works (Georgiev and Georgiev, 2018). Polysemy exhibited slight increase and then noticeable decrease (Figure 3A). This overall decrease of polysemy is consistent with the overall opposite dynamics of Information Content (Figure 3C), which increased compared to the beginning of the conversation. The negative relationship between polysemy and Information Content is theoretically justified by the requirement for additional bits of information needed to specify the intended meaning of polysemous words, which usually could be determined from the context of the conversation.

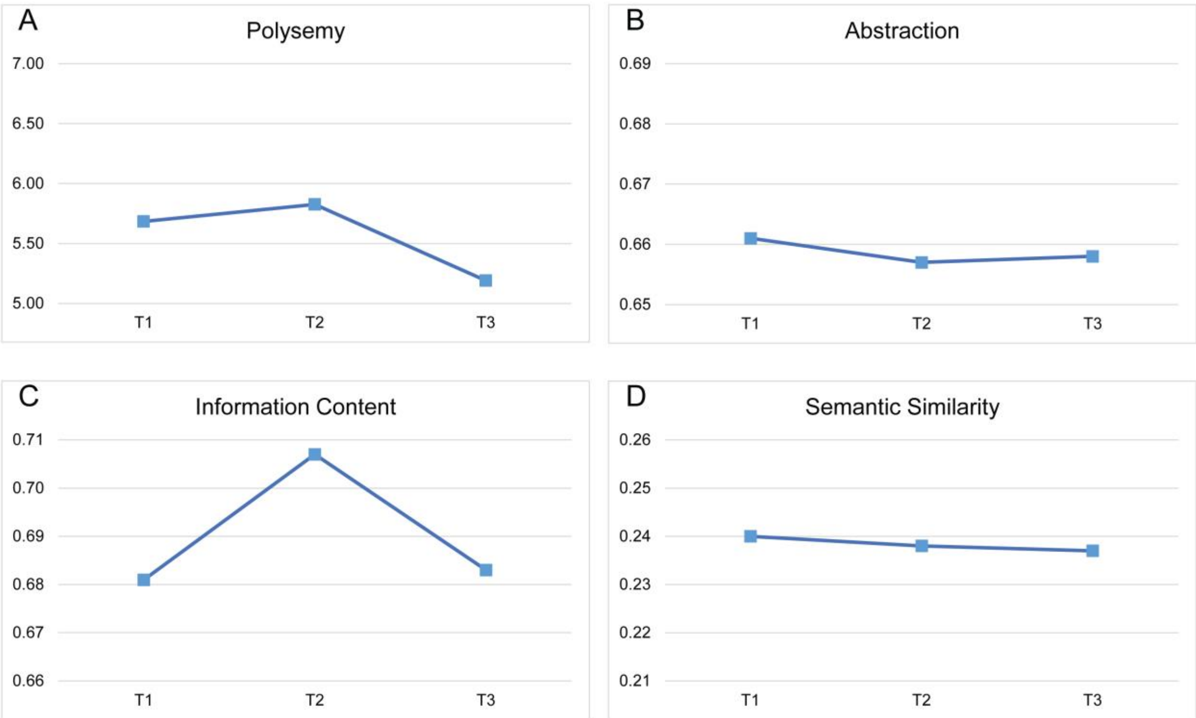

Figure 3. Dynamics of polysemy (A), Abstraction (B), Information content (C) and Semantic similarity (D) of the Concept Design Review (CDR) of the PPP team in the DTRS10 dataset

4.2. Final Design Review (FDR) conversation

The dynamics of the four semantic factors for the Final Design Review (FDR) is shown in Figure 4. The dynamics of the semantic measures for this conversation exhibits very similar behaviour to that of successful ideas reported in our previous work (Georgiev and Georgiev, 2018). Notably, decrease of Polysemy (Figure 4A), increase of Information Content (Figure 4C), and divergent thinking revealed by considerable decrease of Semantic Similarity (Figure 4D), have been all found as attributes of the design conversations that result in successful ideas (Georgiev and Georgiev, 2018). Noteworthy, generated ideas characterized with higher polysemy have a higher tendency to be successfully developed and to exhibit high overall creativity (Georgiev and Taura, 2014). Thus, polysemy appears to contribute to the initial creative association of design ideas, whereas towards the end of the design process the crystalized ideas gain in information content, but combine divergent features as indicated by decreased similarity.

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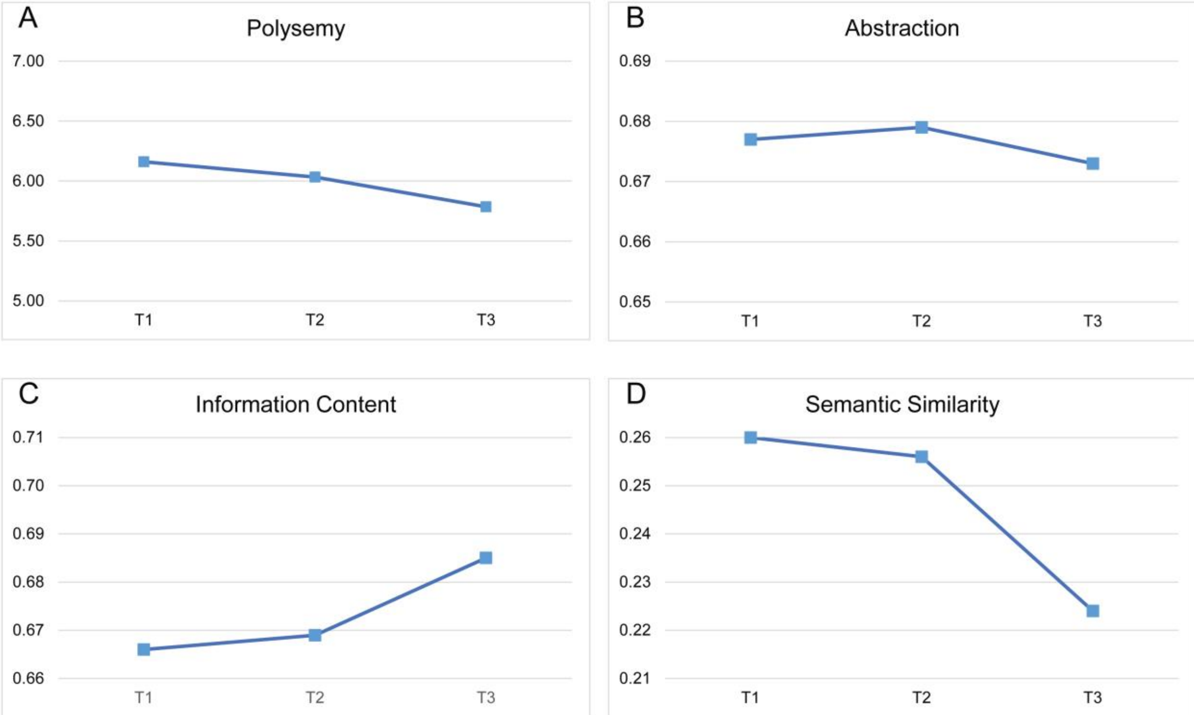

Figure 4. Dynamics of polysemy (A), Abstraction (B), Information content (C) and Semantic similarity (D) of the Final Design Review (FDR) of the PPP team in the DTRS10 dataset

4.3. Competition presentation

The dynamics of the four semantic factors for the Competition presentation is shown in Figure 5. The dynamics of Polysemy (Figure 5A), Information Content (Figure 5C), and Semantic Similarity (Figure 5D) for this conversation exhibits somewhat similar behaviour to the Concept Design Review (CDR).

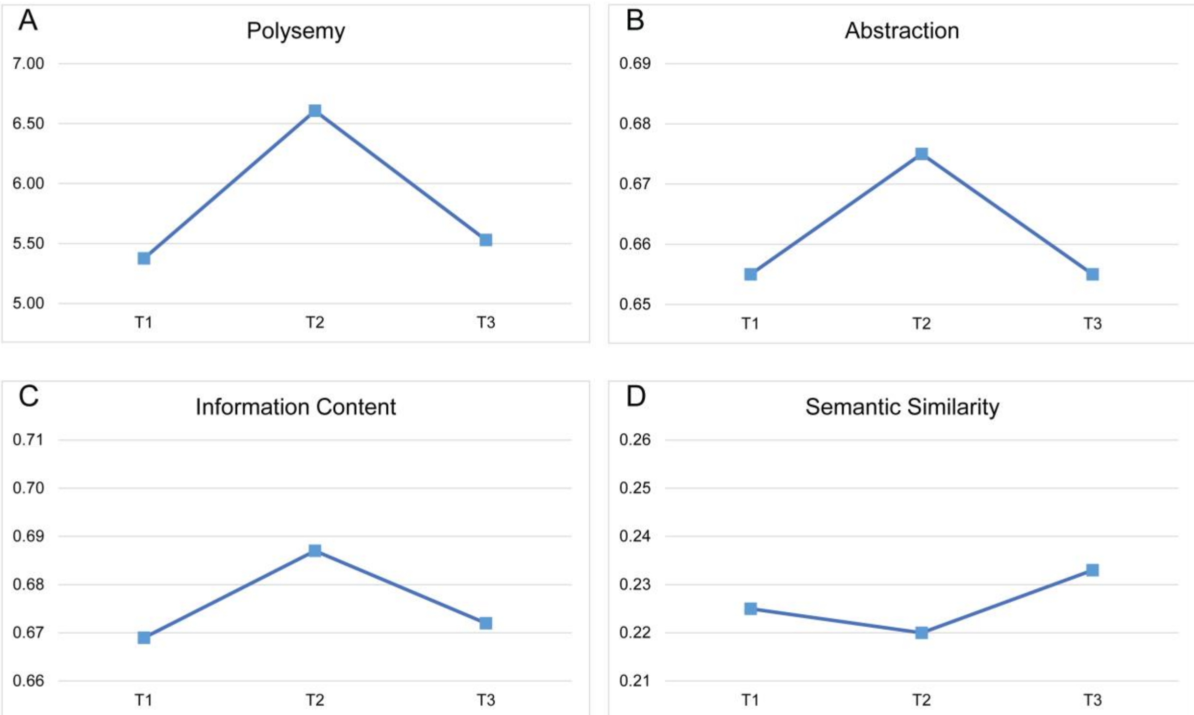

Figure 5. Dynamics of polysemy (A), Abstraction (B), Information content (C) and Semantic similarity (D) of the Competition presentation of the PPP team in the DTRS10 dataset

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5. Discussion

The design conversations of the PPP team can be considered as a case of a successful idea by the criteria applied by Georgiev and Georgiev (2018). Hence, in this paper, we analyse an example of successful engineering design problem solving in educational settings. The three design sessions exhibited distinct time dynamics of semantic factors. Among the three sessions, only the Final Design Review (FDR) conversation of PPP displayed semantic features similar to those pertinent to successful ideas in industrial design education settings (Georgiev and Georgiev, 2018). This similarity is on the level of general trends; however, the case of a single successful design solution available in the Mechanical Engineering data subset is not sufficient for proper statistical analysis or further generalizations.

The method for semantic analysis of conversation transcripts advances design research by providing a tool for objective quantification of time dynamics of engineering design conversations. The semantic factors such as polysemy, abstraction, information content and semantic similarity in problem-solving conversations recorded in educational settings are used to quantify the dynamics of the problem-solving process and reveal convergence/divergence in design thinking. Dynamics of the engineering design problem solving was studied by splitting the conversations into three time points and plotting the data with piecewise linear interpolation. This division provides formal quantification of what occurs in the design problem solving process, potentially allowing objective comparisons of design processes between conversations and between teams/students. Such comparisons can be made in engineering design education settings, allowing automatic evaluations or feedback. In future, implementing knowledge-based systems that analyse design conversations in real-time to identify the semantic measures of designers could quantify and predict fundamental characteristics of the ongoing design process, such as divergence and convergence. As a result, early evaluations of the produced designs could be made.

The presented objective quantitative measures provide a robust tool for quantitative analysis of verbal data. The semantic analysis approach is sufficiently objective to be used by non-experts, a highly desirable feature that addresses one of the shortcomings of methods such as the linkography (Hatcher et al., 2018). The convergence or divergence of semantic similarity in verbalized thoughts appears to reflect the underlying cognitive processes faithfully, including convergent (analytical) or divergent (associative) thinking (Guilford, 1957; Brophy, 2001; Cardoso, et al., 2009; Yoruk and Runco, 2014; Hass, 2017).

Based on the semantic similarity we find evidence of divergent thinking in Final Design Review (FDR) conversation, as opposed to no considerable change of semantic similarity in Concept Design Review (CDR) conversation and overall convergent thinking in the Competition presentation conversation. Previous qualitative studies with DTRS10 dataset point out to convergent feedback of the instructor as most evident one (Yilmaz and Daly, 2016). The early Competition presentation is characterised with more descriptive statements that gradually transfer to more detailed and critical discussion. This transition can be seen from the semantic similarity that indicates initial minimal divergence that is followed by more notable convergence (see Figure 5D).

From the point of view of our objectives to explore the applicability of the semantic analysis approach in engineering design education setup, quantifiable semantic factors such as abstraction, polysemy, information content, and semantic similarity are important for the generation of creative design ideas and for the outcome of a design task (Wilkenfeld and Ward, 2001; Taura and Nagai, 2013). Previous studies have identified the contribution of these four semantic factors, characterising the design conversations from beginning to the end, to the creativity of the design outcomes (Georgiev and Casakin, 2019). The limitations of the approach relate to the limitation of lingual communications, such as possible usage of visual images instead of language at certain creative steps by the designer.

6. Conclusions

In this investigation of the applicability of the semantic analysis approach to the dynamic evaluation of the engineering design problem solving process, we assessed the time dynamics of level of polysemy, abstraction, information content, and semantic similarity (divergence or convergence) in three conversation sessions of a team that delivered successful solution. The quantitative results obtained

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demonstrate that the semantic analysis approach allows for objective evaluation of engineering design problem-solving conversations in educational settings. The approach is straightforward to implement by non-experts and can be utilized for a detailed examination of different solutions or particular conversations pertaining per such solutions, with particular importance for design education. Moreover, the approach allows fast computation of the semantic factors in real time, thus demonstrating the potential for both the analysis and support of the engineering design problem solving process.

Acknowledgements

The authors would like to thank Dr. Robin Adams (Purdue University) for the provided access to the DTRS10 dataset under the signed data-use agreement (Adams, 2015; Adams and Siddiqui, 2013). Great thanks are due to Yazan Barhoush for his role in the implementation of the analysis system and the help with calculation of the sematic measures. This research has been partially financially supported by Academy of Finland 6Genesis Flagship (grant 318927).

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