Comparing the Design Cognition of Concept Design Reviews of Industrial and Mechanical Engineering Designers

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***Abstract**: This paper presents the preliminary results of comparing the design cognition of concept design review conversations of two product design disciplines: industrial design and mechanical engineering design. The comparison is based on a protocol analysis of two concept design review cases using the FBS ontologically-based coding scheme. Inter-disciplinary differences of concept design review were first examined in terms of each review session's focus of cognitive effort expended on reasoning about design problem or design solution. Both review sessions were largely solution-focused, but the industrial design session is relatively more focused on reasoning about the design problem than the mechanical engineering design session. This matches previous findings from cognitive studies into designing processes. When examining the dynamic design cognition, the overall dynamic patterns of concept design review sessions were mainly consistent with the commonalities found in a variety of designing processes, using the measurement of cumulative occurrences of design issues. However, each individual review session's cognitive focus on either reasoning about design problem or solution appeared as constant throughout the review conversations. This implies that concept design review sessions are different from designing sessions. Previous studies into designing processes showed that designers became less focused on the design problem and more engaged in the design solution as designing progressed.*

Keywords: design cognition, design concept review, FBS ontology, protocol analysis

1. Introduction

Design thinking is considered as one of the fundamental ways of thinking and knowing complementary to scientific thinking (Brown and Katz, 2009; Cross, 2008; Cross, 2011; Owen, 2006). This way of thinking is claimed to capture the essential aspects of the activities that designers perform across all design disciplines and domains (Brown & Katz, 2009; Lawson, 2006). Studying design cognition behind the designing processes and identifying the regularities in designing that transcend any specifics of designers or situation could help to elucidate the essence of design thinking.

One of the major challenges to studying this hypothesized regularity of designing is based on the notion that designing is not a singular form of human activity. A variety of activities are embraced under the umbrella of "designing", ranging from formalized engineering design to artistic design. Visser (2006; 2009) argued that designing is "one, but in different forms", i.e., there are both commonalities and differences among the design cognition in different disciplines and situations. Without a deep understanding of the differences due to specific disciplines and situations, our confidence on the regularity beyond those specifics of designing will be limited.

Inter-disciplinary differences of designing are relatively underexplored. A brief summary of some empirical studies into the disciplinary differences and similarities of design cognition is provided in Table 1. All these published studies focused on designers' cognitive effort spent on the designing process that generates design solutions in response to the given requirements. Other forms of design activities, such as design review and critique, have not been adequately studied. This paper aims to extend this inter-disciplinary comparison of designing by studying the design cognition of concept design review conversations. It explores whether the design cognition of design critiques are congruent with those of designing processes.

Table 1. Empirical studies reporting inter-disciplinary differences and similarities of design cognition

Publication	Research Focus	Design disciplines
Akin (2001, 2009)	Variants and invariants of design cognition (e.g., problem decomposition strategies)	Architecture vs Electronic Engineering; vs Engineering design
Kokotovich and Purcell (2000)	Design representation's role in mental synthesis	Graphic Design vs Product Design
Purcell and Gero (1996)	Fixation effect	Industrial Design vs Mechanical Engineering Design
Kan and Gero (2011)	Designers' cognitive efforts	Architecture vs Software Design vs Mechanical Engineering
Jiang, Gero, and Yen (2014)	Cognitive emphasis on reasoning about design problem or design solution	Industrial Design vs Mechanical Engineering Design

2. Ontologically-based protocol analysis

Protocol analysis is one the most commonly applied methodologies for studying design cognition (Cross, Christiaans, & Dorst, 1996; van Someren, Barnard, & Sandberg, 1994). The ad-hoc nature of the development of coding schemes in traditional protocol studies, however, limits their use to the specific cases they have been developed for, and hinders the cross-comparisons and generalizations of the results from different analyses (Gero, 2010). To overcome this limitation, this paper adopts an ontologically-based approach that can be applied in different design situations independent of the specifics of design disciplines, tasks and number of designers (Gero, Kan, & Pourmohamadi, 2011). The discipline-independency of this method enables the cross-comparisons with a variety of previous protocol studies, and makes it possible to discuss the findings of this study in the context of existing design cognition knowledge gained in the prior studies of designing processes.

2.1 Theoretical framework

This ontologically-based protocol analysis methodology is guided by a general design ontology, the Function-Behavior-Structure (FBS) ontology (Gero, 1990; Gero & Kannengiesser, 2004;

Gero & Kannengiesser, 2014; Kruchten, 2005). This ontology claims to describe all designing and designed things in terms of three fundamental ontological constructs: function, behavior, and structure. The function (F) of a designed object is defined as its teleology; the behavior (B) of that object is either derived (Bs) or expected (Be) from the structure, where structure (S) represents the components of an object and their compositional relationships. These ontological constructs are augmented by requirements (R) that come from outside the designer and design description (D) that is the document of any aspect of designing, both R and D are expressible in F, B or S, Figure 1. These six ontological constructs are called "design issues".

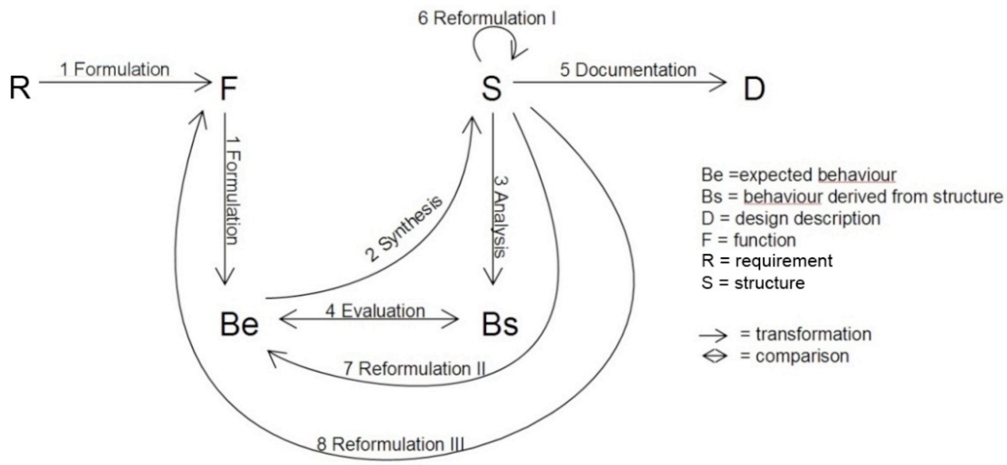

Figure 1. The FBS ontology with the resultants design processes delineated as transitions between the ontological constructs (after Gero & Kannengiesser, 2014)

To apply this ontology in protocol analysis, a discipline-independent coding scheme is developed with six categorical codes developed from the six design issues. The videoed design activities and their transcripts are segmented and coded using these six FBS design issues as codes. A FBS design issue is strictly assigned to only one segment. If an utterance is identified to contain more than one issue, it will be further segmented. Those utterances that do not fit in any of six the FBS categories are marked as others (O). All the O-segments are removed before a coded protocol is further analyzed.

2.2 Measurement of problem-solution (P-S) index

A number of measurements and analysis methods have been developed on the basis of FBS-based segmented and coded protocols (Pourmohamadi & Gero, 2011). This paper applies the two measurements of problem-solution (P-S) index and cumulative occurrence of design issues. Both measures are independent of the length of the design session, as well as the number of participating designers. This allows the comparison of design protocols with different numbers of segments and participants.

The problem-solution (P-S) index is a meta-cognition concept and measures the cognitive focus on reasoning about either the design problem or the design solution (Jiang et al., 2014). It first categorizes the coded design issues into problem-related issues (requirement, function and expected behavior) and solution-related issues (behavior from structure and structure) based on a division of reasoning about the design problem and the design solution. The design description issue is not specified within the problem-solution division. It is thus excluded in the analyses of P-S indexes.

The index is then calculated as the ratio of the summed frequency of problem-related issues over the summed frequency of solution-related issues, Equation (1). A P-S index value of greater than 1 indicates the designer expended more cognitive effort on reasoning about design problem than the design solution. A P-S index of less than 1 means the designer is relatively more focused on reasoning about design solutions than about the design problem.

$$\text{P-S index} = \frac{\sum(\text{Problem-related issues})}{\sum(\text{Solution-related issues})} = \frac{\sum(R,F,Be)}{\sum(Bs,S)} \qquad (1)$$

2.3 Measurement of cumulative occurrence of design issue

The cumulative occurrence of a design issue is formally defined in Equation (2). At a given segment i, the occurrence of the issue x (x_i) is counted as 1 if this segment is coded as x, or 0 otherwise. The cumulative occurrence of issue x is then calculated as a summed x_i from the beginning of a protocol to the current segment n, Figure 2. On the basis of this cumulative occurrence of design issues, two quantitative and two qualitative measurements and analysis methods have been developed, Table 2.

$$c = \sum_{i=1}^{n} x_i \qquad (2)$$

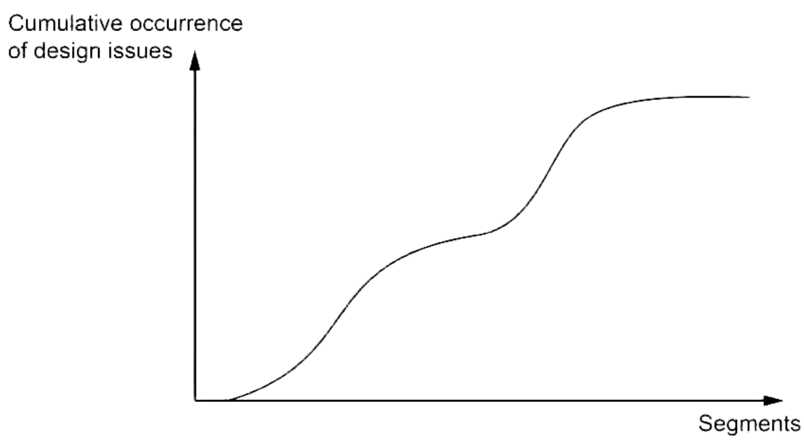

Figure 2. Graphical representation of cumulative occurrence of design issue in a design protocol (source: Gero, Kannengiesser, & Pourmohamadi, 2014)

Table 2. Measurements based on cumulative occurrence of design issues*

Measurement	Qualitative/quantitative	Explanation
Slope	Quantitative	Slope of the best-fit line, measuring the rate at which design issues are generated.
R^2	Quantitative	The graph of cumulative occurrence of an issue is linear when $R^2 \geq 0.950$
First occurrence at start	Qualitative	Whether this issue is considered from the start of the design session.

Continuity	Qualitative	Whether this issue is considered throughout designing or only up to a certain point.

* Source: Gero et al. (2014)

2.4 Previous findings: Commonalities and differences across designing

The previous FBS ontologically-based protocol analyses have produced empirical evidence of some commonalities and inter-disciplinary differences of design cognition across different designing processes.

Commonalities across designing

- While designing progresses, a design session's P-S index decreases independent of design disciplines and situations (Gero, Jiang, & Williams, 2013; Jiang et al., 2014);
- The timeline graphs of cumulative occurrence of structure, behavior from structure, expected behavior and description demonstrate a linearity while the graphs of requirement and function do not exhibit linearity (Gero et al., 2014).

Disciplinary differences between industrial design and mechanical engineering design

- Using the P-S index as the measure, industrial designers generally spend more cognitive effort on reasoning about the design problem than mechanical engineering designers do (Jiang et al., 2014);
- Derived from Gero et al. (2014), the industrial design sessions' timeline graphs of cumulative occurrence of problem-related issues (function and expected behavior) generally contain a higher slope for the line of best fit, while the mechanical engineering design sessions have a higher slope for the best-fit line of cumulative solution-related issues (structure and behavior from structure).

3. Data analysis: A case study

3.1 Data source

This paper is based on two videoed cases of concept review sessions of "Industrial Design (Graduate)" and concept design review (CDR) sessions of "Mechanical Engineering" available as part of the dataset of DTRS10 (Adams & Siddiqui, 2013). Two design review conversations were chosen as case studies for this exploratory analysis, Figure 3. During these two review sessions, design students presented their early design works to their tutor and gained feedback in the form of concept design reviews or critiques.

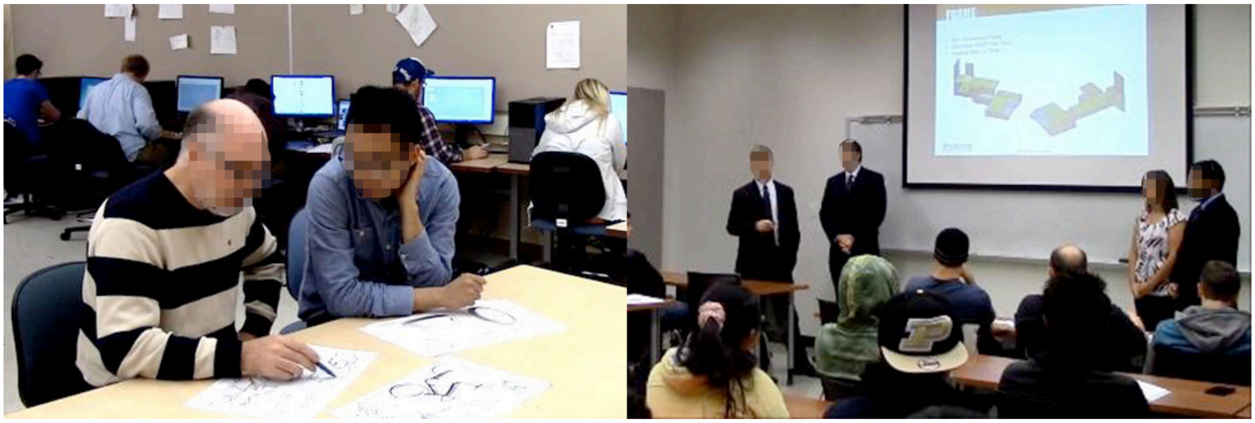

Figure 3. Screenshots of concept design review conversations (left: ID critique; right: ME critique)

3.2 Frequency of design issues

After the transcripts of the videos were segmented and coded, these two cases of concept design review conversations, industrial design (ID) and mechanical engineering design (ME), resulted in two sequences of design issues containing 342 segments and 307 segments respectively. The frequency distributions of design issues are shown in Figure 4. The total occurrence of requirement issue in each session is less than 10 issues in terms of absolute frequency and less than 3% of total issues in terms of relative frequency. Thus, the requirement issue is excluded from the analysis of cumulative occurrence of design issues, due to the small number of data points.

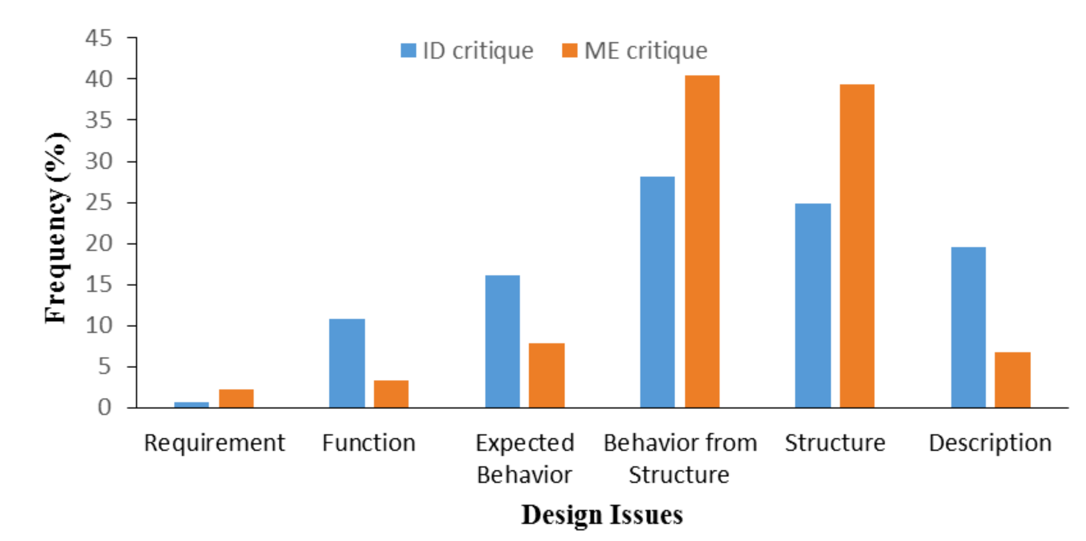

Figure 4. Frequency distribution of design issues

3.3 Results on the basis of problem-solution index

The P-S index values of the whole concept design review session as well as of the first and second halves of the review session are shown in Table 3. In general, these two design review sessions are solution-focused, indicated by the P-S Indexes being less-than-one. The inter-disciplinary differences of these two review sessions are revealed by inter-row comparisons in

Table 3. It shows that, for each column, the value of ID review session's P-S index is almost triple that of the ME session. This finding agrees with previous findings from studies into designing that, compared to mechanical engineering designers, industrial designers expend more of their cognitive effort reasoning about the problem than the solution (Jiang et al., 2014).

Table 3. Summary of problem-solution index

Protocol	**Problem-solution index**		
	Whole session	1st half of the session	2nd half of the session
ID critique	0.52	0.51	0.53
ME critique	0.17	0.17	0.17

The trend that design cognition develops through each review session is illustrated by the comparison between the first half and second half of the critique sessions (third and fourth columns of Table 3). It indicates that, for both concept design review conversations, there are no differences between the first half and second half of the session. This finding contradicts the trend found in multiple previous studies into designing, in which the P-S index value of the second half of the session was significantly lower than the P-S index of the first half of the session (Gero et al., 2013; Jiang et al., 2014).

We then divided the whole session into deciles for a more detailed examination of the change in the P-S index as the review session progresses. A simple linear regression model was used to model the decile P-S indexes. The slopes of the regression line (the line of best fit) is used to depict the increasing or decreasing trend of designers' cognitive focus on reasoning about design problem. Table 4 shows that, for both sessions, the slope of the sequential P-S indexes' best-fit lines is not significantly different from 0. Although P-S indexes fluctuate, there is no increasing or decreasing trend identified throughout the review session.

Table 4. Sequential P-S index calculated on the basis of 10 deciles of the protocol

Protocol	*t* statistic	*p* value	95% CI for the slope
ID critique	0.408	0.694	-0.064 ~ 0.091.
ME critique	-0.646	0.536	-0.054 ~ 0.030.

3.4 Results on the basis of cumulative occurrence of design issue

The results of the analysis of cumulative occurrence of design issues are tabulated in Table 5. The shadowed rows show the reference values constructed from studies of the same discipline reported in Gero et al. (2014). Most measurements of cumulative occurrences of design issues in concept design review conversations are consistent with their counterparts observed in the designing sessions. In particular, the linearity of cumulative expected behavior issues, behavior from structure issues and structure issues are the same as these commonalities while designing. This indicates that, similar to the situation in designing sessions, these design issues were also focused on at a nearly constant rate throughout the whole review conversation, Figure 5.

Table 5. Quantitative and qualitative measurements related to the cumulative occurrence of design issues for case study and previous studies

Protocol		Slope	R^2	First occurrence at start	Continuity	Shape
ID critique	Function	0.099	0.966	Yes	Yes	Linear
		0.064 ~ 0.271	0.745 ~ 0.884	Yes	No	Non-Linear*
	Expected Behavior	0.181	0.978	Yes	Yes	Linear
		0.150 ~ 0.530	0.930 ~ 0.993	Yes	Yes*	Linear*
	Behavior from Structure	0.279	0.991	Yes	Yes	Linear
		0.079 ~ 0.254	0.928 ~ 0.992	No*	Yes	Linear*
	Structure	0.247	0.992	Yes	Yes	Linear
		0.287 ~ 0.336	0.990 ~ 0.993	Yes	Yes	Linear
ME critique	Function	0.008	0.439	Yes	No	Non-Linear
		0.019 ~ 0.034	0.830 ~ 0.960	Yes	No*	Non-Linear
	Expected Behavior	0.084	0.987	No	Yes	Linear
		0.056 ~ 0.110	0.929 ~ 0.984	Yes*	No*	Linear*
	Behavior from Structure	0.398	0.993	Yes	Yes	Linear
		0.179 ~ 0.352	0.982 ~ 0.997	Yes*	Yes	Linear
	Structure	0.435	0.993	Yes	Yes	Linear
		0.417 ~ 0.476	0.998 ~ 0.999	Yes	Yes	Linear

Shadowed rows: reference value calculated from Gero et al. (2014)
* for the majority of relevant protocols

A further examination of the tabulated data of each issue's cumulative occurrence measurements in Gero et al. (2014) indicates that the slope value could be used to examine inter-disciplinary difference between two design review sessions. A larger slope value indicates this issue occurs more frequently during the design session. Figure 5 shows that the industrial design review session has a higher slope value for the problem-related issues of function and expected behaviors. While the ME review session showed higher slope values for the solution-related issues of structure and behavior from structure issues. These results are congruent with previous findings that industrial designers tend to be more problem-focused than mechanical engineering designers (Jiang et al., 2014).

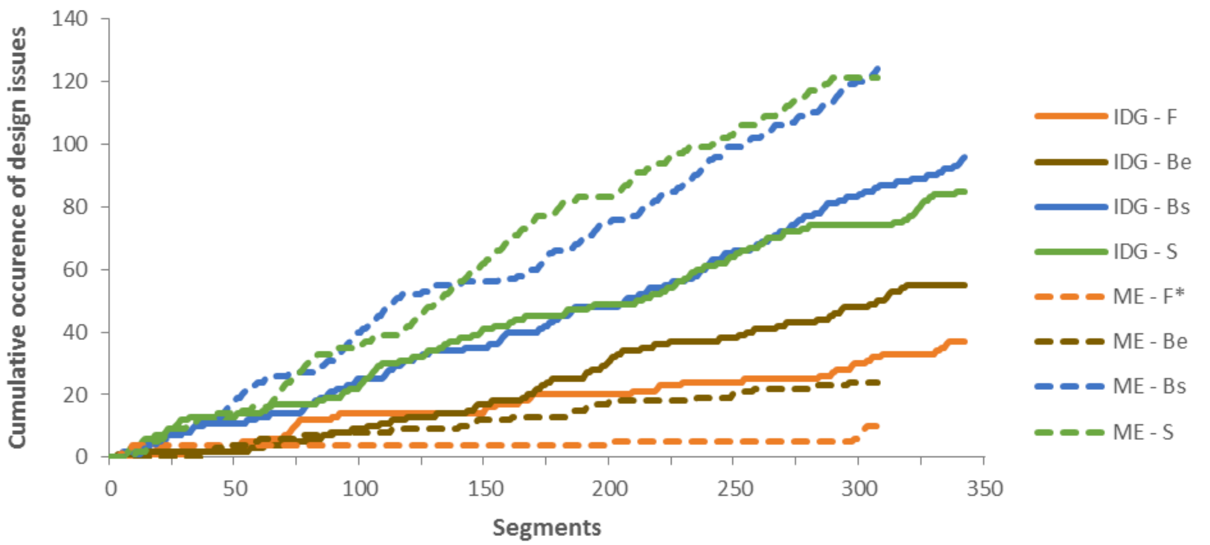

Figure 5. Cumulative occurrence of design issues in the observed concept design review conversations. IDG = industrial designers, ME = mechanical engineers.
* Non-linear

4. Discussion and Conclusion

This paper extends the exploration of commonalities and differences of design cognition into the field of concept design review conversations, by comparing two cases of industrial design and mechanical engineering design review sessions. Based on these preliminary findings, the inter-disciplinary differences of design review sessions are mainly consistent with the patterns found in prior studies of commonalities and differences between industrial designers and mechanical engineers while designing. Industrial designers are generally more problem-focused than mechanical engineering designers in both designing and review sessions.

Some commonalities of designing are also found to occur in the design review scenarios, such as the cognitive effort expended on the structure issue and the behavior from structure issue has a constant rate throughout the whole session. However, the cognitive shift from reasoning about design problem to more focused on design solution in designing is not found in these two design review cases. The concept design review sessions seem to be more solution-focused than designing sessions. This finding is not unexpected given that design critiques are mainly conducted around the assessment of design solutions.

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