ICoRD '13
International Conference
on
Research into Design
Indian Institute of Technology Madras, Chennai, 7 - 9 January, 2013.

Exploring A Multi-Meeting Engineering Design Project

John S. Gero

Krasnow Institute for Advanced Study, George Mason University
Fairfax, USA
Email: john@johngero.com

Jiang, Hao

Division of Industrial Design, National University of Singapore
Email: jiangh82@gmail.com

Sonia Da Silva Vieira

TuDelft / IDMEC-FEUP Faculty of Engineering, University of Porto
Email: S.L.DaSilvaVieira@tudelft.nl

Abstract: This paper presents the results of a protocol analysis of a case study of a multi-meeting engineering design project lasting about five months. The project involved an engineering consultancy for the design of a robot controller. The design team members consisted of engineers with different backgrounds. Eight sequential design meetings were studied. The video recordings of these meetings were transcribed and then segmented and coded using an ontologically-based coding scheme. The analysis of these meetings focused on differences in the distributions of design issues and syntactic design processes between adjacent meetings. Statistically significant differences between a number of adjacent meetings were observed. These differences are taken to indicate critical design decisions made in those meetings.

Keyword : multi-meeting project, protocol analysis, FBS ontology

1 Introduction

The overwhelming majority of studies of engineering design, whether they are conducted in the laboratory or in the office, are of single meetings. There are a few studies of engineering design that involve two meetings. In practice most design projects are spread out over time and involve the design team in multiple meetings. It is important to study such multi-meeting projects both to determine differences in design behavior between multi-meeting and single meeting design projects and differences in design behavior between meetings. This paper reports on the results of comparing adjacent meetings of a case study of a multi-meeting engineering design project.

Elucidating design activities and the cognitive processes underlying design behaviors has been the focus of an increasing of research studies, e.g., [1, 2]. Protocol analysis has become the dominant methodology in these studies [1, 2, 3]. Since protocol analysis is a resource intensive methodology with a high ratio of analysis time to observation time, the observed design activities were usually of a limited duration, ranging from a few minutes to one or two hours [4]. An emerging trend in design cognition research is towards studying “naturally occurring design activity in authentic settings” [5]. Authentic design projects usually last a few weeks or months. It may not be practical to directly apply the existing methods focusing on the observation scale of minutes or hours. Some adaptions were made by reducing the resolution of observation, e.g., omitting the minute-by-minute details, to track a longer design project [6, 7, 8]. This kind of method, however, is not recommended for research into design cognition, as it fails to capture the transient cognitive events and interactions/transitions between intermediary thoughts.

Another form of adaptation was proposed in the “design meeting protocols” workshop, using a small number of design meetings to represent a much larger design process [5]. Two examples were demonstrated in this workshop: an architectural and an engineering design case. Each case consists of two meetings recorded from the same projects. Design meetings should provide an appropriate sampling technique for an authentic design project since: (1) meetings are a common form of authentic design activity, (2) they are usually located in critical stages of a project and important to decision-making, and (3) practically, meetings are well-bounded which leads to a manageable size of dataset for analysis [5]. The two meetings presented in this workshop do not adequately reflect what occurs in design practice, where multiple meetings over a long time span are often needed to complete a design project. This paper thus continues the investigation of design meetings as a sampling technique for a lengthy design project, by studying eight sequential meetings recorded in an engineering robotic controller design project lasting five months.

2 An Engineering Design Project

In this engineering design case study, eight sequential meetings took place during a period of observation of five months for the design of a robot controller. This project was the subject of a research project developed in collaboration with a design team of engineers with different backgrounds in mechatronics, namely: software/hardware, control, aerospace and electronics engineering. The design was based on a previous similar robotic controller nevertheless the team faced several unexpected situations and challenges. Table 1 provides an overview of the meetings, their lengths, topics, team members’ attendance and qualitative division of the eight meetings into two fundamental stages.

Each of these meetings had a duration of approximately one hour. In the first month, three meetings were dedicated to analyzing and clarifying specifications and production planning. In the second month a fourth meeting initiated the testing and detailing tasks that lasted until the end of the observation period. The three meetings in the last two months focused more on evaluations of problems, detailing and testing. Issues of specification analysis, connection systems, power supply, costs, and identification and analysis of problems were mostly discussed in these meetings.

Table 1 Overview of meetings during the design of a robot control

Month		1st			2nd	3rd	4th		5th
Meeting		1	2	3	4	5	6	7	8
Duration		1h: 06min	1h: 03min	1h:08min	52min	34min	51: 40min	1h: 01min	58min
Topic		Detailed discussion about the specifications and solutions	Planning, outsourcing and power supply	Discussion about the internal communication of the robot	Assembly of sub-parts, connections, testing and details	Discussion of software, defining tests and connections	Identification of problems, connections and detail	Complete assembly, Identification of problems, detailing and testing	Identification of problems, detailing and testing
Stage		Clarifying specifications, Production planning			Concept generation, Evaluations of problems, Detailing and Testing				
Team member*	LR	√	√	√	√	√	√	√	√
	EE	√	√	√	√	√	√	√	√
	SE	√	√	√		√	√	√	√
	TC	√	√		√	√	√	√	√

* **LR**: Leading researcher, **EE**: Electronics Engineer, **SE**: Software Engineer, **TC**: Technician

3 Ontologically-based Protocol Analysis

Each these eight meetings was videotaped, the utterances in them transcribed and the transcriptions converted into a sequence of design issues using a principled coding scheme developed from a design ontology, i.e., the Function-Behavior-Structure (FBS) ontology [9, 10]. The FBS ontology models designing by three classes of ontological variables: 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 classes are augmented by requirements (R) that come from outside the designer and description (D) that is the document of any aspect of designing, Figure 1.

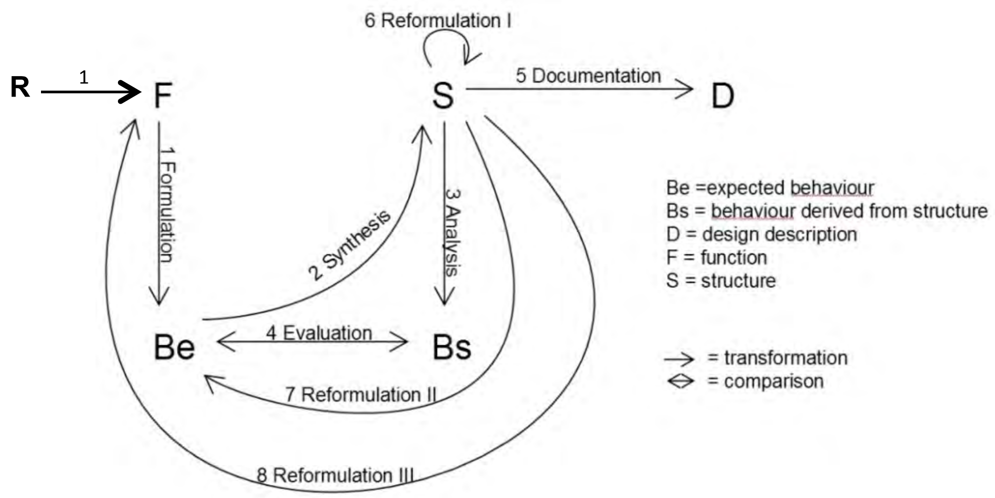

Figure 1 The FBS ontology (after [10])

The FBS ontologically-based coding scheme consists of these six codes, each represents a particular aspect of design cognition. Application of this coding scheme can segment and encode the meeting videos (i.e., design conversations and gestures, etc.) into a sequence of design issues denoted with semantic symbol, i.e., the FBS codes. The transitions between adjacent design issues were then defined as eight types of syntactic design processes, as numbered in Figure 1 [2].

The transformed data of these eight design meetings, namely eight sequences of design issues and syntactic design processes, became the foundational data for subsequent analyses. Design cognition is multifaceted. Design issues and syntactic design processes measure two orthogonal dimensions of design cognition, respectively responding to the content-oriented and process-oriented analyses of design cognition.

4 Method of Analysis

Each design meeting's frequency distributions of design issues and syntactic processes summarize the overall characteristics of design cognition manifested in that meeting. The cognitive differences between two meetings can be examined by Pearson's Chi-square test for independence. When a statistical significance is identified ($p< 0.05$), Cramer's V coefficient is calculated as the effect size to describe the relative strength of the difference between two meetings' issue/process distributions. The value of Cramer's V varies from 0 to 1. This study used the value of 0.10 as the threshold to indicate a substantive difference [11, 12].

The cross tabulations (here referred to as cross tabs) are then used as a *post hoc* test to further investigate which specific design issue(s) or syntactic process(es) contributes to the overall cognitive differences between two meetings. Adjusted residuals in a cross tab provide an estimation of the differences between observed and expected values (by assuming the distributions under comparisons are identical to each other). The design issues/processes with a high absolute value of adjusted residuals (greater than or equal to 2) indicate that designers are more engaged in those aspects of design cognition in the meeting corresponding to the positive cells, than the other one.

5 Results

5.1 Coding Results

This paper presents preliminary coding results carried out by a single coder. The frequencies of design issues and syntactic processes were normalized by converting them into percentages; this eliminates the different lengths of the design meetings and the subsequent different number of segments in each meeting, Figure 2.

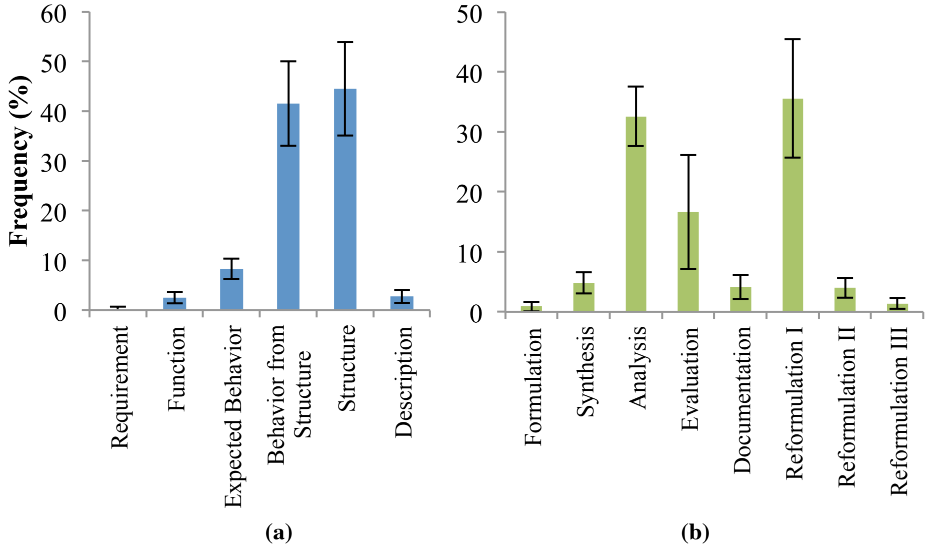

Figure 2 Frequency distribution of (a) design issues and (b) syntactic design processes

The distributions of design issues, Figure 2(a), indicate that, in each meeting, the majority of design issues were structure and behavior from structure. These two solution-related issues represented about 85% of total issues. The requirement issues, i.e., input from outside of the design teams, on the other hand, were negligible in this project, only occupying 0.23% of the total issues. The requirement issue was thus excluded in the following Chi-square analysis of design issue distributions.

The most frequent syntactic design processes, shown in Figure 2(b), were associated with reasoning about the solution space, namely the processes of reformulation I (M = 35.59, SD = 9.91), analysis (M = 32.59, SD = 4.96) and evaluation (M = 16.65, SD = 9.54). Three problem-related processes, i.e., formulation, reformulation II (of expected behaviors) and reformulation III (of functions), consumed less cognitive effort; each was less than 5% of the total processes. They were thus combined as a single category in the Chi-square analysis of syntactic process distributions.

5.2 Cognitive Shifts between Two Adjacent Meetings

The analysis of cognitive progress during the 5-month observation was undertaken by comparing the cognitive changes between two adjacent meetings. The Chi-square test results are summarized in Table 2. Three significant cognitive shifts were identified: from Meeting 3 to Meeting 4; from Meeting 6 to Meeting 7; and from Meeting 7 to Meeting 8. Post hoc tests indicate that Meetings 7 and 8 mainly differed in the description issue and documentation process, rather than essential aspects of design cognition. The remainder of this paper thus focuses on the first two transitions of the sequential meetings.

Table 2 Comparisons of issue/process distributions of adjacent meetings

Comparison	Distr. of issue/ process	*df*	Chi-square statistics	*p*-value	Cramer's V
Meeting 1 vs 2	issue	4	5.162	0.271	0.092
	process	5	5.835	0.323	0.123
Meeting 2 vs 3	issue	4	12.902	0.012 *	0.134
	process	5	5.704	0.336	0.112
Meeting 3 vs 4	issue	4	19.712	0.001 **	0.169
	process	5	27.161	0.000 ***	0.263
Meeting 4 vs 5	issue	4	7.631	0.106	0.124
	process	5	11.739	0.039 *	0.207
Meeting 5 vs 6	issue	4	1.907	0.753	0.065
	process	5	0.973	0.965	0.060
Meeting 6 vs 7	issue	4	20.423	0.000 ***	0.173
	process	5	30.06	0.000 ***	0.282
Meeting 7 vs 8	issue	4	9.522	0.049 *	0.113
	process	5	12.429	0.029 *	0.187

* $p<0.05$, ** $p<0.01$, *** $p<0.001$

5.2.1 Cognitive transition between Meetings 3 and 4

The comparisons of specific design issues and syntactic design processes between Meetings 3 and 4 are presented in two cross tabs, Tables 3 and 4. Meeting 3 was more engaged in the generative aspect of design cognition, indicated by significantly higher percentages of structure issue and the syntactic design process of reformulation of structure (reformulation I). Meeting 4 then shifted to behavioral aspect of design cognition, indicated by higher percentages of expected behavior and behavior from structure issues, as well as the syntactic design process of evaluation.

Table 3 Comparison of the design issue distributions of Meetings 3 and 4, significant differences are highlighted in bold

Design Issue \ Meeting #		Meeting 3	Meeting 4	Total
Function	Count	17	10	27
	% within the meeting	5.0	2.8	3.9
	Adjusted Residual	1.5	-1.5	
Expected Behavior	Count	25	46	71
	% within the meeting	7.4	13.1	10.3
	Adjusted Residual	-2.5	**2.5**	
Behavior from Structure	Count	123	163	286
	% within the meeting	36.5	46.4	41.6
	Adjusted Residual	-2.6	**2.6**	
Structure	Count	166	124	290
	% within the meeting	49.3	35.3	42.2
	Adjusted Residual	**3.7**	-3.7	
Design Description	Count	6	8	14
	% within the meeting	1.8	2.3	2.0
	Adjusted Residual	-.5	.5	
Total	Count	337	351	688
	% within the meeting	100.0	100.0	100.0

Table 4 Comparison of the syntactic design process distributions of Meetings 3 and 4, significant differences are highlighted in bold

Syntactic Design Process \ Meeting #		Meeting 3	Meeting 4	Total
(Re-) Formulation	Count	17	10	27

of Function & Expected Behavior	% within the meeting	8.5	5.2	6.9
	Adjusted Residual	1.3	-1.3	
Synthesis	Count	9	12	21
	% within the meeting	4.5	6.3	5.3
	Adjusted Residual	-.8	.8	
Analysis	Count	61	55	116
	% within the meeting	30.3	28.6	29.5
	Adjusted Residual	.4	-.4	
Evaluation	Count	21	56	77
	% within the meeting	10.4	29.2	19.6
	Adjusted Residual	-4.7	**4.7**	
Documentation	Count	6	7	13
	% within the meeting	3.0	3.6	3.3
	Adjusted Residual	-.4	.4	
Reformulation I (of Structure)	Count	87	52	139
	% within the meeting	43.3	27.1	35.4
	Adjusted Residual	**3.4**	-3.4	
Total	Count	201	192	393
	% within the meeting	100.0	100.0	100.0

Cognitive transition between Meetings 6 and 7

The cognitive shift between Meetings 6 and 7 is further articulated in Tables 5 and 6. Resembling the previous cognitive change between Meetings 3 and 4, the latter meeting shifted from an emphasis on generative aspect of design cognition (indicated by higher percentages of structure issue and the process of reformulation I) to engage more in the evaluative aspect of design cognition (indicated by higher percentages of behavior from structure issue and the processes of analysis and evaluation).

Table 5 Comparison of the design issue distributions of Meetings 6 and 7, significant differences are highlighted in bold

Design Issue \ Meeting #		Meeting 6	Meeting 7	Total
Function	Count	6	9	15
	% within the meeting	2.0	2.4	2.2
	Adjusted Residual	-.3	.3	

Expected Behavior	Count	23	31	54
	% within the meeting	7.7	8.1	7.9
	Adjusted Residual	-.2	.2	
Behavior from Structure	Count	111	202	313
	% within the meeting	37.0	53.0	46.0
	Adjusted Residual	-4.2	**4.2**	
Structure	Count	155	134	289
	% within the meeting	51.7	35.2	42.4
	Adjusted Residual	**4.3**	-4.3	
Design Description	Count	5	5	10
	% within the meeting	1.7	1.3	1.5
	Adjusted Residual	.4	-.4	
Total	Count	300	381	681
	% within the meeting	100.0	100.0	100.0

Table 6 Comparison of the syntactic design process distributions of Meetings 6 and 7, significant differences are highlighted in bold

Syntactic Design Process \ Meeting #		Meeting 6	Meeting 7	Total
(Re-) Formulation of Function & Expected Behavior	Count	11	6	17
	% within the meeting	5.8	3.2	4.5
	Adjusted Residual	1.2	-1.2	
Synthesis	Count	8	5	13
	% within the meeting	4.2	2.6	3.4
	Adjusted Residual	.8	-.8	
Analysis	Count	58	83	141
	% within the meeting	30.7	43.9	37.3
	Adjusted Residual	-2.7	**2.7**	
Evaluation	Count	25	51	76
	% within the meeting	13.2	27.0	20.1
	Adjusted Residual	-3.3	**3.3**	
Documentation	Count	5	4	9
	% within the meeting	2.6	2.1	2.4
	Adjusted Residual	.3	-.3	

Reformulation I (of Structure)	Count	82	40	122
	% within the meeting	43.4	21.2	32.3
	Adjusted Residual	**4.6**	-4.6	
Total	Count	189	189	378
	% within the meeting	100.0	100.0	100.0

6 Discussion

The engineers in this design project had previous experience in designing robot controllers. Many robotic components, such as the microcontroller, and battery were continuously discussed from the first meeting on. This may explain the descriptive statistics result that solution-related design issues and solution-related syntactic design processes constituted the majority of design reasoning in all the eight meetings. The two significant cognitive changes identified in this case study were shifting from a relative focus on the solution generation to an increased focus on the analysis and evaluation of the proposed solutions.

The quantitative comparisons were then triangulated with qualitative assessments of the individual meetings. Meeting 3 focused on the discussion of structure components introduced in Meeting 1. Similar to Meeting 7, Meeting 3 did not continue the topics raised in Meeting 2. The control aspects of the robot are introduced in the next meeting. Meeting 4 seemed to be a "bridge meeting", discussing some design considerations more in depth, attempting to make connections to other considerations. This may explain that, in this meeting, the cognitive effort spent on reasoning about structure decreased, while the meeting was more focused on the expected consequence of solutions.

Meeting 6 was mainly targeted at a particular technical problem “how to solve the overheating of the board". A number of alternative solutions were proposed accordingly. Due to the focus on this topic, the percentages of the structure issue and the syntactic process of reformulation I increased in this meeting compared to the previous meetings.

There was a topic shift between Meetings 6 and 7. The latter meeting did not continue the topics raised in Meeting 6. Rather, it reactivated the topics introduced in Meetings 1 and 4, such as CPU and batteries, during the testing process. Behavioral and evaluative aspects of design cognition thus became the focus of this meeting. Later studies will present detailed analyses of design cognition during the critical situations leading to design decisions.

7 Conclusion

This paper presents a preliminary analysis of a multi-meeting engineering design project lasting five months during which there were eight design meetings. Design projects in practice regularly involve multiple meetings and it is important in the development of the understanding of designing that such multiple meeting design projects be studied and comparisons made with single meeting design projects to determine differences. The increased scale of observation, compared to a single design session of one or two hours in most design protocol studies, provides a more nuanced understanding of designing as can be seen in the statistically significant differences found between a number of the design meetings.

When the eight meetings are aggregated into a single set of measurements of design issues and syntactic design processes, the design issues and syntactic design processes distributions follow the general behavior observed in the single design sessions used in studies of designing [13, 14] masking any detailed behavioral differences that occur over time. This points to the need for a more detailed study of multi-meeting designing.

Multiple meetings with time gaps provide opportunities for incubation that are not directly available in single meeting design sessions [15, 16]. Incubation plays a role in all areas of human cognition but insufficient is known about the design cognition of incubation. Studies of multiple meetings of professional designers in practice are an alternate to laboratory studies of the cognition of incubation. They may provide the basis of insight into incubation in designing.

Later papers will present detailed comparisons of design cognition derived from multi-meetings with the behavior observed in single meeting design sessions. The findings in this paper are based on a preliminary coding of the meetings and need to be confirmed.

Acknowledgments

This research is supported in part by a grant from the US National Science Foundation Grant No. IIS-1002079, and by the FCT-Portuguese Foundation of Science and Technology, which is thankfully acknowledged. The authors gratefully acknowledge the Delft Center for Systems and Control for supporting this research.

References

1 Cross, N., Christiaans, H., and Dorst, K., "Analysing design activity". John Wiley & Sons Ltd, 1996.

2 Gero, J.S., "Generalizing design cognition research," in *Dtrs 8: Interpreting design thinking*, Dorst, K., Stewart, S.C., Staudinger, I., Paton, B., and Dong, A., Eds., ed University of Technology Syndey, 2010, pp. 187-198.

3 Jiang, H. and Yen, C.C., "Protocol analysis in design research: A review," "Design | Rigor & Relevance", International Association of Societies of Design Research (IASDR) 2009 Conference, pp. CD un-numbered, 2009.

4 Bainbridge, L. and Sanderson, P.M., "Verbal protocol analysis," in *Evaluation of human work: A practical ergonomics methodology (3rd edition)*, Wilson, J.R. and Corlett, E.N., Eds., 3rd ed Boca Raton, Florida: Taylor & Francis, 2005, pp. 159-184.

5 McDonnell, J. and Lloyd, P., Eds., "About: Designing: Analysing design meetings". CRC Press, 2009.

6 Waldron, M.B. and Waldron, K.J., "A time sequence study of a complex mechanical system design," Design Studies, vol. 9, pp. 95-106, 1988.

7 Rowe, P.G., "Design thinking". MIT Press, 1987.

8 Rowe, P.G., "A priori knowledge and heuristic reasoning in architectural design," Journal of Architectural Education, vol. 36, pp. 18-23, 1982.

9 Gero, J.S., "Design prototypes: A knowledge representation schema for design," AI Magazine, vol. 11, pp. 26-36, 1990.

10 Gero, J.S. and Kannengiesser, U., "The situated function-behaviour-structure framework," Design Studies, vol. 25, pp. 373-391, 2004.

11 Crewson, P. “Applied statistics handbook” (version 1.2). Available: http://www.acastat.com/statbook.htm, 2011

12 Dancey, C.P. and Reidy, J., "Statistics without maths for psychology", 5th ed. Prentice Hall/Pearson, 2011.

13 Kan, J.W.T. and Gero, J.S. “Using the FBS ontology to capture semantic design information”, in J. McDonnell and P. Lloyd (eds), DTRS7, University of the Arts, London, pp 155-165, 2007

14 Williams, C. B., Gero, J. S., Lee, Y. and Paretti, M. “Exploring the effect of design education on the design cognition of mechanical engineering students”, ASME IDETC2011 DETC2011-48357, 2011

15 Smith, S.M. and Dodds, R.A., “Incubation”, *in* MA Runco and SR Pritzker (eds), Encyclopedia of Creativity, Vol.2, Associated Press: pp 39-44, 1999

16 Smith, S. and Blankenship, S. “Incubation and the persistence of fixation in problem solving”, American Journal of Psychology, Vol. 104, pp 61-87, 1991.