The Decomposition/Recomposition Design Behavior of Student and Professional Engineers

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Decomposition/Recomposition Design Behavior of Student and Professional Engineers: A Pilot Study

Introduction

Design activity has significant differences from other cognitive activities while there are similarities in design activities conducted in various conditions (Visser, 2009). Design is also recognized as the critical element of engineering thinking, which differentiates engineering from other problem solving approaches (Dym, Agogino, Eris, Frey & Leifer, 2005). One of the primary goals of engineering design education is to equip students with the capability to become expert design engineers.

Design expertise "has some aspects that are significantly different from expertise in other fields" (Cross, 2004, p. 427). Researchers study design expertise via a number of different methodologies within a framework of the expert-novice continuum. By investigating the differences between experts and novices, researchers gain a deeper understanding of the differences in design thinking patterns between novices and expert designers (Kavakli & Gero, 2002; Harlim & Belski, 2013).

Among the engineering skills required, engineering design is fundamental for engineering graduates since engineering design is a major task in engineering practice. The use of design strategies plays a significant role in engineering design, and a commonly used strategy is problem decomposition/recomposition. It is frequently used by experienced engineers, especially when dealing with complex engineering problems (Dym & Brown, 2012; Vincenti, 1990). Problem decomposition and problem recomposition is widely used in design activities to simplify the problem (Akin, 2001; Buede & Miller, 2016; Krishnamoorty & Rajeev, 1996). The process of problem decomposition involves breaking the design problem into smaller independent sub-problems (Arvanitis, Todd, Gibb, & Orihashi, 2001). Each sub-problem can be further broken into even smaller problems (Arvanitis et al., 2001) and the decomposition process stops when designers can directly approach each sub-problem. Problem recomposition is a bottom-up process that follows problem decomposition. It is the process of recomposing all sub-solutions (Chandrasekaran, 1990) based on the premise of satisfying requirements of the combined design (Hall, Jackson, Lanney, Nuseibeh, & Rapanotti, 2002). Instead of focusing on a complex design problem as a whole, engineers can work on several smaller, more approachable sub-problems using this process, which makes the process of engineering design more efficient (Liikkanen & Perttula, 2009).

Akin (1986) extensively discussed the use of decomposition in design cognition. There are two principles in decomposition: functional principle and measurable principle (Li, Yi, & Tang, 2011). Studies have identified a gap between engineering novices and engineering experts when it comes to problem decomposition/recomposition skills in engineering design (Ball, Evans, & Dennis, 1994; Ho, 2001).

Methodology

In order to study the differences in decomposition/recomposition strategies between student and professional engineers a protocol analysis approach was adopted to obtain empirically-based evidence for any differences.

Protocol analysis is a rigorous methodology for eliciting verbal reports of thought sequences as a valid source of data on thinking. It is a well-developed, validated method for the acquisition of data on thinking (Ericsson & Simon, 1993; Van-Someren, Barnard & Sandberg, 1994). It has been used extensively in design research to assist in the development of the understanding of the cognitive behavior of designers (Atman & Turns, 2001; Badke-Schaub, Lauche, Neumann & Ahmed, 2007; Christensen & Schunn, 2007; Gericke, Schmidt-Kretschmer & Blessing, 2007; Kavakli & Gero, 2002; McDonnell & Lloyd, 2007; McNeill, Gero & Warren, 1998; Purcell & Gero, 1998; Suwa, Gero & Purcell, 1998; Tang & Gero, 2002; Williams, Gero, Lee & Paretti, 2011). There are two types of protocol analysis: think aloud and retrospective (Ericsson & Simon, 1993). Subjects are required to verbalize what they are thinking when performing the task in a think aloud protocol.

The think aloud protocol is also called Verbal Protocol Analysis (VPA). Researchers started to use it in psychological research in the 1920s for examining problem solving. With the development of technology, audio and video became part of VPA to provide more accurate recording. Ericsson and Simon's text (Ericsson & Simon, 1993) laid the foundation for most modern studies using VPA. They studied the validity of this research method and concluded that VPA could collect data accurately without affecting the performance of the subjects observed. They also indicated that thinking aloud might slow down the working process but that the subjects' thinking was not interfered with by thinking aloud unless they were asked to provide more information.

The basic methodology of the protocol analysis method consists of the following sequence of tasks that were followed for this project. project.

Design problem. All dyads completed the same open-ended engineering design challenge. The design challenge used was a double-hung window opener that assisted the elderly with raising and lowering windows. This challenge had been used by other researchers to study engineering design (Williams et al., 2011; Lammi & Becker, 2013). There were various engineering and social constraints in this challenge, which made it a typical engineering design challenge. In addition, double-hung windows are commonly used and most students were familiar with window operation and function so they did not need advanced engineering knowledge to complete the design challenge.

The design dyads were given following descriptions of the problem:

"Your design team has been approached by a local nursing home to design a new product to assist its elderly residents.

The nursing home administrators have noticed that changes in humidity during the summer months cause the windows of the 65-year old building to "stick," thus requiring significant amounts of force to raise and lower the window panes. The force required to adjust the windows is often much too large for the nursing home tenants, making it very difficult for them to regulate their room temperature.

Your team has been tasked with designing a device that will assist the elderly tenants with raising and lowering the building's windows. You will produce a complete engineering design solution for the client. Someone should be able to build the device from your solution without any questions. Since each window is not guaranteed to be located near an electrical socket, this device should not rely on electric power.

The building's windows are double-hung, Figure 1. The double-hung window consists of an upper and lower sash that slide vertically in separate grooves in the side jambs. This type of window provides a maximum face opening for ventilation of one-half the total window area. Each sash is provided with springs, balances, or compression weather stripping to hold it in place in any location."

Figure 1. Double hung window

During the design session, participants had access to only five websites related to the design challenge. The five websites included the construction of double-hung window, a YouTube video about the mechanism of double hung windows, a website about American Disabilities Act (ADA) information, a website of ADA Accessibility Guidelines for Buildings and Facilities (ADAAG), and a Wikipedia webpage about American with Disabilities Act of 1990. Participants had limited web access to prevent them from searching for solutions to the design problem on other web sites.

Coding development. In typical protocol analyses the researchers commence with a pre-existing coding scheme and modify it based on the task and events in the current protocol. In this project we will use a principled coding scheme based on the FBS ontology developed by Gero and colleagues (Gero, 1990; Gero & Kannengiesser, 2004). The FBS ontology contains three types of variables: Function (F), Behavior (B) and Structure (S). Function (F) represents the design intentions or purposes of the design; behavior (B) represents the object's attributes that can be either directly derived from a representation of the object (Bs) or expected to be derived from a representation of the object (Be); and structure (S) which represents the components that make up an object and their relationships. The model is augmented by two external design issues that do not require an extension of the ontology itself as they can be represented as either F, B or S: requirements (R) and descriptions (D). The first of these represents requirements from outside design and the second, descriptions, mean the documentation of the design. Figure 2 shows the FBS ontology and the consequential eight design processes (labelled by number) that make up designing—formulation (1), synthesis (2), analysis (3), evaluation (4), synthesis, description (5) and reformulation I (6), II (7), III (8). Formulation defines the process that produces a function ie sets up expected goals from the existing requirement, while synthesis generates a structure as a candidate solution. Analysis produces a behavior from the existing structure and evaluation compares the behavior derived from structure with the expected behavior to determine the effectiveness of the candidate solution. Reformulation is the process from the structure back to itself, behavior or function, which is a reconstruction or reframing process. Among the eight design processes, the three types of reformulation processes are suggested to be the dominant processes that potentially capture creative aspects of designing by introducing new variables or new directions. By calculating the transitions between design issues, various analyses can be conducted. The two papers that describe the foundations of the FBS ontology have been widely referenced with over 2,500 citations (scholar.google.com, accessed August 17, 2016). The FBS ontology produces six codes for the design issues and transformations between those six codes for the design issues produce eight design processes, Tables 1 and 2.

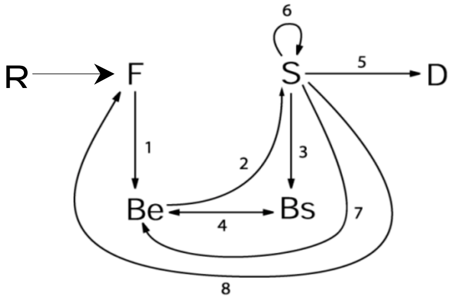

Figure 2. The FBS ontology with its consequential ontology of design processes, labeled 1 through 8.

Table 1

FBS Design Issues Codes

Code	*Design issue*
R	Requirement
F	Function
Bs	Behavior from the structure
Be	Expected behavior
S	Structure
D	Documentation

Table 2

FBS Design Processes

Design Processes	
Formulation (1)	R>F, F>Be
Synthesis (2)	Be>S
Analysis (3)	S>Bs
Evaluation (4)	Be<>Bs
Documentation (5)	S>D
Reformulation I (6)	S>S
Reformulation II (7)	S>Be
Reformulation III (8)	S>F

Videoing of participants. This involves capturing voice, sketching and gestures. Experience demonstrates that all three of these need to captured to allow for a robust data source for the later segmentation and coding. The result is a time-stamped video of the design session. Two cameras can be used; one focused on the participants and one on the drawing surface.

Transcription of verbalization into text. Various voice-to-text programs have been tried in order to automate this activity without much success with a team of designers because of the variability of the voices. As a consequence, this transcription process is a manual task that results in a time-stamped, text version of the verbalizations in a session.

Segmentation of the transcription. Segmentation involves collecting into a single unit those verbalizations that cohere with each other. In this project segmentation is be on the basis of individual design issues represented by the FBS codes. Each segment can contain only one code. An example of a segmentation and coding is shown in Table 3 (Kan & Gero, 2009). This harmonizes all segmentation when using this coding scheme since there is now an *isomorphism between segments and codes*. This is a critically important advance in protocol analysis since the two separate processes of segmentation and coding of segments are now linked. The segments can be connected to time through the time-stamped text constituents of the segments.

Table 3

Example segmentation, with 6 segments based on the FBS coding

Code	*Segment*
R	(reads requirements) it need only be temporary
F	Does it need to be storable?
Be	It should be able to rotate 90 degrees.
S	If we have a ball joint here
Bs	That will be expensive
S	What about a hinge?

Arbitration of segmentation/coding. Two segmenters/ coders are used to produce the final segmented/coded protocol in order to have robustness, which is measured by inter-coder reliability against the final, arbitrated protocol. Typical inter-coder reliability obtained by this method is in the range 75–80%. The result is the final, arbitrated protocol. This final protocol is the first data set available for analysis. The final protocol for a 60-minute design session may generate between 400 and 1,500 segments. This provides a rich and statistically significant data set for each protocol collected.

The final, arbitrated protocol consists of a sequence of design issues represented by a sequence of FBS codes. From this list we can build a variety of statistical models that represent the cognitive behavior of the participants. In this paper we report only tabular statistical models and use them in making statistical comparisons between student and professional engineers' decomposition and recomposition behavior.

This study selected participants using a convenience sampling method (Gall, Gall & Borg, 2007). Fifty participants took part in the study: 20 college engineering freshmen, 20 college engineering seniors, and 10 engineering professionals. Engineering professionals had at least 10 years design experiences in the industry. All of the participants worked in dyads. This research was a pilot study with a small industry participant sample size. Results of the quantitative data show preliminary findings only, and need to be confirmed with a larger cohort of engineering professionals to have statistical generality.

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Participants were given one hour to complete the engineering design challenge. Instead of presenting practical products by the end of design, participants were required to only submit design proposals as their final outcome. There was no instruction about the form or the content of the proposals they would submit. They did not build, test, and analyze their designs because of the time constraint.

After participants completed the design challenge, audio data from the video were transcribed, segmented, and coded. Two coders were involved in coding data. The coders were trained using sample data from previous studies before coding data. The inter-coder reliability was calculated among coders to examine the reliability of coding. After the training session the overall agreement between coders and the arbitrated coding was above 80%.

After the process of transcribing, the utterances were segmented. The segmentation was based on design issues. Each segment can only contain one design issue resulting in a single code for each segmented utterance. For example, if multiple sentences focused on the same design issue, those sentences were segmented as one segment. If a sentence contained multiple design issues, the sentence was segmented further into multiple segments.

The coding system had two dimensions: FBS ontology and "levels of the problem" that is a decomposition of the FBS ontology, which did not require any change in the ontology. The FBS ontology represented the design issues during the design process. The second dimension of the coding system was the hierarchical level of the problem. The level of problem is used in representing the decomposition and recomposition (Gero and McNeill, 1998). Engineers decomposed the design problem into multiple sub-problems and work on each sub-problem in order to produce a solution. Three levels of the problem were used, represented as 1 to 3. Definitions and examples of level of problem are shown in Table 4. Ho (2001) used a similar coding system to investigate engineering design strategies used by individual electrical engineers. The FBS framework had the following codes: function (F), expected behavior (Be), behavior from the structure (Bs), structure (S), documentation (D), and requirement (R). Utterances that were not related to designing were coded as "other" (O).

Since the numbers of utterances generated by each dyad were different, the percentages of occurrences of the codes were used to normalize the results to allow for comparisons of differences between the two cohorts of students and professionals.

Table 4

Definitions and Examples of Level of Problem

Utterance	*Level of Problem*	*Definition*
Whatever we come up with has to be cheaper than replacing the window, right?	1: System	Designers consider the problem as an integral whole.
You know maybe instead of applying the force the resistance is to keep it closed and when you release it, it naturally tries to open.	2: System and subsystems	Designers consider interactions between subsystems.
These are usually, the bottom one opens on the inside right?	3: Subsystems	Designers consider details of the subsystems.

Table 5 shows an example of the coding into design issues and levels from one dyad's utterances. The level of the problem designers worked on transitioned across the different levels through the design session. When the level of the problem transitions from a higher level to a lower level, it is classified as problem decomposition, and when it transitions from a lower level to a higher level, it is classified as problem recomposition.

Table 5

Examples of Problem Decomposition and Problem Recomposition Coding

Subject	*Utterance*	*FBS Code*	*Level Code*	*Decomposition/ Recomposition*
A	Not what I'm asking, but like how in-depth?	F	1	–
A	Because that's like how I'm in senior drawing ...	O	–	–
A	Like a pulley is just something you go to the store and buy. Like you… You know...Based on, like	S	3	D
A	I don't we are given all the numbers that we need to be able to figure what type of pulley system or what gear ratio.	S	3	-
B	Yes, and the cost of materials	B	1	R

Results and analyses

The data of engineering freshmen, engineering seniors, and engineering professionals were analyzed and no statistically significant differences were found between engineering freshmen and engineering seniors. Therefore, the data of engineering freshmen and engineering seniors were combined to provide a larger sample size.

Full Design Sessions. The means and standard deviations of the problem decomposition and problem recomposition activities of the student and professional cohorts are shown in Table 6. The results show that in general, the use of decomposition and recomposition is the same within each cohort and different between students and professionals. To determine whether the apparent differences between the two cohorts are significant independent sample t-tests were applied. Table 7 shows the results of these t-tests.

Table 6
The Distribution of Decompositions and Recompositions: Full Design Sessions

	Students		*Professionals*	
	Mean	*SD*	*Mean*	*SD*
Problem decomposition	.154	.029	.223	.030
Problem recomposition	.154	.028	.225	.035

Statistical significant differences were found in using problem decomposition and problem recomposition between students and professional engineers. Based on these results, professionals used 50% more problem decomposition and 50% more problem recomposition than students, which is a significant difference.

Table 7
Statistical Comparisons of Problem Decomposition and Recomposition Between Students and Professionals: Full Design Sessions

Comparison	*p value*
Problem decomposition	<0.01**
Problem recomposition	<0.01**

*$p \leq 0.05$
**$p \leq 0.01$

In spite of differences in research settings, the results of this study are consistent with Ho's results (Ho, 2001). Both studies suggest that there continues to be a gap in using problem decomposition/recomposition between students and professionals.

Dividing Design Sessions Into Halves. In order to obtain a more nuanced understanding of these differences the design sessions were split into halves to see if there were differences in behavior between the first half and the second half of the design sessions, i.e., across time. The distribution of data when the design sessions were split in halves is shown in Table 8. The results of statistical tests,, are similar to the results for the full sessions except that there is a drop in the magnitude of the statistical significant difference between the first and second halves. During the first half of the design process, students were found to use less problem decomposition and problem recomposition than professionals. The same applied in the second half but at a relatively different rate.

Table 8
The comparison of Data: Design Sessions Divided Into Halves

	Students		*Professionals*		
	Mean	*SD*	*Mean*	*SD*	*p value*
Problem decomposition (first half)	.080	.017	.130	.010	<0.01**
Problem recomposition (first half)	.080	.018	.130	.011	<0.01**
Problem decomposition (second half)	.074	.020	.094	.022	.030*
Problem decomposition (second half)	.075	.019	.095	.028	.034*

*$p \leq 0.05$
**$p \leq 0.01$

Table 8 also shows that the distributions of problem decomposition and problem recomposition are not equal between the first half and the second half for both students and professionals. In order to see if there are any statistical significant differences between the use of problem decomposition and problem recomposition between the full session and the two halves, a series of statistical comparisons was undertaken whose results are shown in Tables 9 and 10. These results show that there are differences between the first and second halves of the design sessions for both students and professionals.

Table 9

Statistical Comparisons of Students and Professionals Between Problem Decomposition and Problem Recomposition: Design Sessions Divided Into Halves

	p value
First half – professionals	.046*
First half – students	.048*
Second half – professionals	.047*
Second half – students	.042*

*$p \leq 0.05$

Table 10

Statistical Comparisons of Students and Professionals Between Problem Decomposition and Problem Recomposition: Full Design Sessions

	p value
Professionals	.046*
Students	.046*

*$p \leq 0.05$

The ratios of decomposition and recomposition in the first half to that the second half were calculated, which are shown in Table 11. The ratios presented are means of the first half divided by means of the second half. Since these ratios are not the same for professionals and students the results indicate that there is a difference in behavior between these two cohorts over time.

Table 11

Ratio of First Half to Second Half of Design Sessions for Decomposition and Recomposition

Cohort	*Ratio First half/Second half*
Professionals - problem decomposition	1.382
Professionals - problem recomposition	1.369
Students - problem decomposition	1.080
Students - problem recomposition	1.058

The ratios of decomposition and recomposition of the professionals with students is presented in Table 12. These results show that both students and professionals used problem decomposition and problem recomposition more during the first half of the design sessions indicated by the value of the ratio being greater than one. In the first half of the design process, professionals used problem decomposition 38% more than the second half while students used problem decomposition 8% more than the second half. The results are similar for problem recomposition. Professionals used this strategy 37% more in the first half while students used the strategy 6% more in the first half. These results show that there are differences in design thinking behavior between students and professionals. Professionals tended to use the strategy of problem decomposition and recomposition more in the first half of the design process while students tended to use this strategy uniformly through the entire design process uniformly.

Table 12

Ratio of Professionals to Students of Halves of Design Session for Decomposition and Recomposition

	Professionals/Students
First half - problem decomposition	1.625
First half - problem recomposition	1.639
Second half - problem decomposition	1.270
Second half - problem recomposition	1.267

Table 13

The Comparison of Transitions – First Half

Transitions	*Students*		*Professionals*		
	Mean	*SD*	*Mean*	*SD*	*p value*
1 to 2	.006	.003	.012	.010	.021*
1 to 3	.028	.007	.041	.012	<0.01**
2 to 3	.045	.017	.076	.025	<0.01**
3 to 2	.046	.017	.079	.025	<0.01**
3 to 1	.026	.008	.037	.012	.023*
2 to 1	.007	.005	.015	.012	.035*

*$p \leq 0.05$

**$p \leq 0.01$

Levels. The structure of problem decomposition includes 3 types of transitions: transitions from Levels 1 to 2, transitions from Levels 1 to 3, and transitions from Levels 2 to 3. Similarly, the structure of problem recomposition includes 3 types of transitions as well. They are: transitions from Levels 3 to 2, transitions from Levels 3 to 1, and transitions from Levels 2 to 1. In order to further explore the design thinking of students and professionals, the processes of problem decomposition and problem recomposition were examined in more detail by calculating the distributions of these transitions into different levels.

The distribution of transitions in the first half of the design sessions when the data were broken into levels is presented in Table 13. The means of all types of transitions of professionals are higher than those of the students, except the transition from Level 1 to Level 2. The last column in Table 13 shows the results of statistical significance tests. Statistical significant differences were found at all levels. This result presents further detail and confirms that in the first half of the design process, professionals tended to use more problem decomposition and problem recomposition on all levels.

Table 14 shows the distribution of transitions in the second half of the design sessions when the data were broken into levels. The means of all types of transitions of professionals are higher than those of the students. The last column in Table 14 shows the results of statistical significance tests. Statistical significant differences were not found for any transitions. This result indicates that in the second half of the design sessions the distributions of transitions between levels for professionals and students are statistically similar. When exploring the data of the whole design session, statistical differences were found but it did not indicate where the differences occurred. From the results presented in Tables 14, we can conclude that most differences exist in the first half while the design behavior in the second half are similar for engineering professionals and students. These differences are hidden when analyzing the whole design session.

Table 14

The Comparison of Transitions – Second Half

Transitions	*Students*		*Professionals*		
	Mean	*SD*	*Mean*	*SD*	*p value*
1 to 2	.006	.008	.010	.003	.335
1 to 3	.021	.008	.025	.010	.361
2 to 3	.047	.012	.059	.012	.053
3 to 2	.048	.012	.059	.016	.111
3 to 1	.020	.009	.027	.008	.115
2 to 1	.007	.006	.009	.007	.515

$^{*}p \leq 0.05$

$^{**}p \leq 0.01$

The ratios of the mean decompositions and recompositions by levels of the first half of the design sessions to the second half of the design sessions for students and professionals are given in Table 15. These ratios are a quantitative measure of the differences between the first and second halves of the design sessions. When the value is greater than 1 then there is more decomposition/recomposition activity in the first half than in the second half and when it is less than 1 the opposite is true.

Table 15

Ratio of First Half to Second Half of Design Session of Decomposition And Recomposition Transitions – Students and Professionals

Transitions	*Ratio First half/Second half - Students*	*Ratio First half/Second half - Professionals*
1 to 2	.994	1.213
1 to 3	1.377	1.675
2 to 3	.962	1.289
3 to 2	.959	1.338
3 to 1	1.312	1.364
2 to 1	1.031	1.586

For students, the ratios of decomposition from Level 1 to Level 2 and from Level 2 to Level 3 are lower in the first half than the second half (as the ratios are less than 1). However, the ratio of recomposition from Level 3 to Level 1 is higher in the first half than the second half (as the ratio is greater than 1). This indicates a lack of symmetry between decomposition and recomposition.

The results in Table 15 show that professionals exhibit a different behavior to students in that all the ratios are greater than 1. This indicates that the problem decomposition /recomposition strategies of professionals are all greater in the first halves of the design sessions than in the second halves.

Conclusions

This pilot study analyzed the design thinking of cohorts of both engineering professional and engineering students. A difference between the design behavior of students and professionals in using problem decomposition and problem recomposition was found in this study. This difference was further analyzed and students were found to use significantly less problem decomposition and problem recomposition than engineering professionals in general. They use the strategies significantly less in the first half of the design process. This differences was further analyzed by breaking the strategy by transitions among different levels of the problem which provides an understanding of the use of decomposition/recomposition across different levels of the problem.

This pilot study provides foundational results to help understand the engineering design cognition of the strategy of decomposition/ recomposition of students and professionals and measures the differences between these two cohorts. This study presents empirical evidence that engineering professionals used the strategy of problem decomposition and problem recomposition more than students in the engineering design process. In addition, professionals used the strategy more in the first half of the design session than in the second half while students tended to use the strategy evenly through the entire design session.

This study has contributed to the body of research related to engineering expertise. By comparing the process of problem decomposition and problem recomposition between dyads of students and professionals, it has helped better understand the characteristics of expertise in engineering design.

In addition to providing a better understanding of students' and professionals' design cognition, the results of this study suggest that problem decomposition and problem recomposition may be valuable to engineering educators, as the results, if generalizable, are helpful to develop more "expert-like" design behaviors in students by educational interventions that increase their decomposition and recomposition while designing through a modification of the engineering curriculum. By identifying differences between student and professional design behavior we can move toward interventions in teaching to reduce such differences. The conclusion of the study provides an empirical foundation for engineering educators to develop teaching models and activities to promote using problem decomposition and recomposition in engineering education on the basis that professional engineers use more decomposition/recomposition that students currently do.

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