Investigating Student Misconceptions in the Design Process Using Multidimensional Scaling

Ruth A. Streveler, Ronald L. Miller
Colorado School of Mines

Abstract

In this study, multidimensional scaling (MDS) was used to investigate how chemical engineering seniors view the concept of "design" at the beginning and end of a capstone design course. We discuss how the MDS results may indicate where students possess misconceptions about "design" and how this information can be used to improve design instruction in the classroom.

Introduction

The design process is a cornerstone of engineering and is a common subject of engineering education research [1]. How well do chemical engineering seniors, on the threshold of their professional careers, "know" this key concept? How can engineering education tell if students misunderstand the concept? These are the questions tackled by this study.

A basic premise of our work is that the concept "design" cannot be viewed in isolation. Research in cognitive psychology has well established that people learn by creating a network of meanings among concepts [2]. For example, a person who thinks of the word "dog," might view that term in connection with terms relating to other domesticated animals, with memories about the family dog, with certain knowledge about the behavior of dogs. These networks of meanings are sometimes called "cognitive structures." These cognitive structures do not remain static, but change as one becomes more expert in a field. For example, Chi and her associates found that novices in physics (college freshmen enrolled in a physics course) used superficial characteristics (such as the presence of a pulley) to categorize physics problems, while experts in physics (professors and PhD students) categorized the same physics problems according to deeper characteristics, such as the principles used to solve the problems (for example, Newton's Second Law of Motion) [3].

Are the connections made in one's cognitive structure ever incorrect? From a scientific view point the answer is "Definitely." Educational researchers often call "incorrectly" connected terms "misconceptions." A great deal of education research has been devoted to the study of misconceptions, and how these "faulty" ideas hamper students from learning scientifically correct information [4]. An example of a misconception often held by engineering students is that a chemical reaction stops when equilibrium is reached.

Given the assumptions that people create cognitive structures, that some of the connections within cognitive structures may be misconceptions, and that these structures change over time, we then address the problem of understanding how students view the concept “design” by looking at: 1) how various terms related to design may be linked, 2) how these links may change over time and 3) how these links compare to the way an “expert,” in this case the instructor, feels the terms are related.

How can one document cognitive structure? In this study we use multidimensional scaling (MDS) to measure cognitive structure and look for “incorrect” connections that may signal the presence of misconceptions. Multidimensional scaling [5] is the name for a family of methods that convert similarity judgments into physical distance. The first step in MDS analysis is to ask participants to group together terms that they believe are conceptually linked. This information is averaged and converted to a similarity matrix that is then input to the MDS procedure for analysis. Much as regression analysis finds an equation which best fits a set of data points, MDS analysis finds a model (in 2 to n dimensions) that is the best fit of the similarity matrix. In the MDS results, items seen as similar to one another will be plotted closely together. One can look at the MDS output, see which items students view as belonging together, and gain insight into how students are organizing the information they are learning. If the MDS analysis reveals terms clustered together “incorrectly” this may signify a potential misconception.

Methods

Participants in our study were 23 chemical engineering seniors enrolled in a capstone senior design course at the Colorado School of Mines. As stated above, we used MDS to measure the students’cognitive structure. The following steps were used to conduct this study.

1) The course professor selected terms that were deemed to be central to understanding chemical engineering design. The 32 terms selected by the instructor for the clustering task are listed in Table 1.

2) In order to increase the ease of use, a method of gathering the clustering data on-line was developed and used in this study. As shown in Figure 1, a web page was created which listed the 32 terms in alphabetical order. Radio buttons allowed students to cluster the terms into one of nine possible groups.

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Table 1. Design terms, selected by the instructor and used by students in the clustering task.

Term number	Term name
Term 1	capital cost
Term 2	cash flow analysis
Term 3	conceptual design
Term 4	debottlenecking
Term 5	design heuristic
Term 6	economic optimum
Term 7	energy transfer block
Term 8	engineering design process
Term 9	engineering judgment
Term 10	equipment heuristic
Term 11	generic block flow diagram
Term 12	HAZOP analysis
Term 13	input-output diagram
Term 14	life-cycle analysis
Term 15	maintenance cost
Term 16	operating cost
Term 17	operating heuristic
Term 18	piping and instrumentation diagram
Term 19	process analysis
Term 20	process bottleneck
Term 21	process evaluation
Term 22	process flow diagram
Term 23	process optimization
Term 24	process simulation
Term 25	process synthesis
Term 26	rate of return
Term 27	reaction block
Term 28	risk analysis
Term 29	separation block
Term 30	technical optimum
Term 31	time value of money
Term 32	troubleshooting

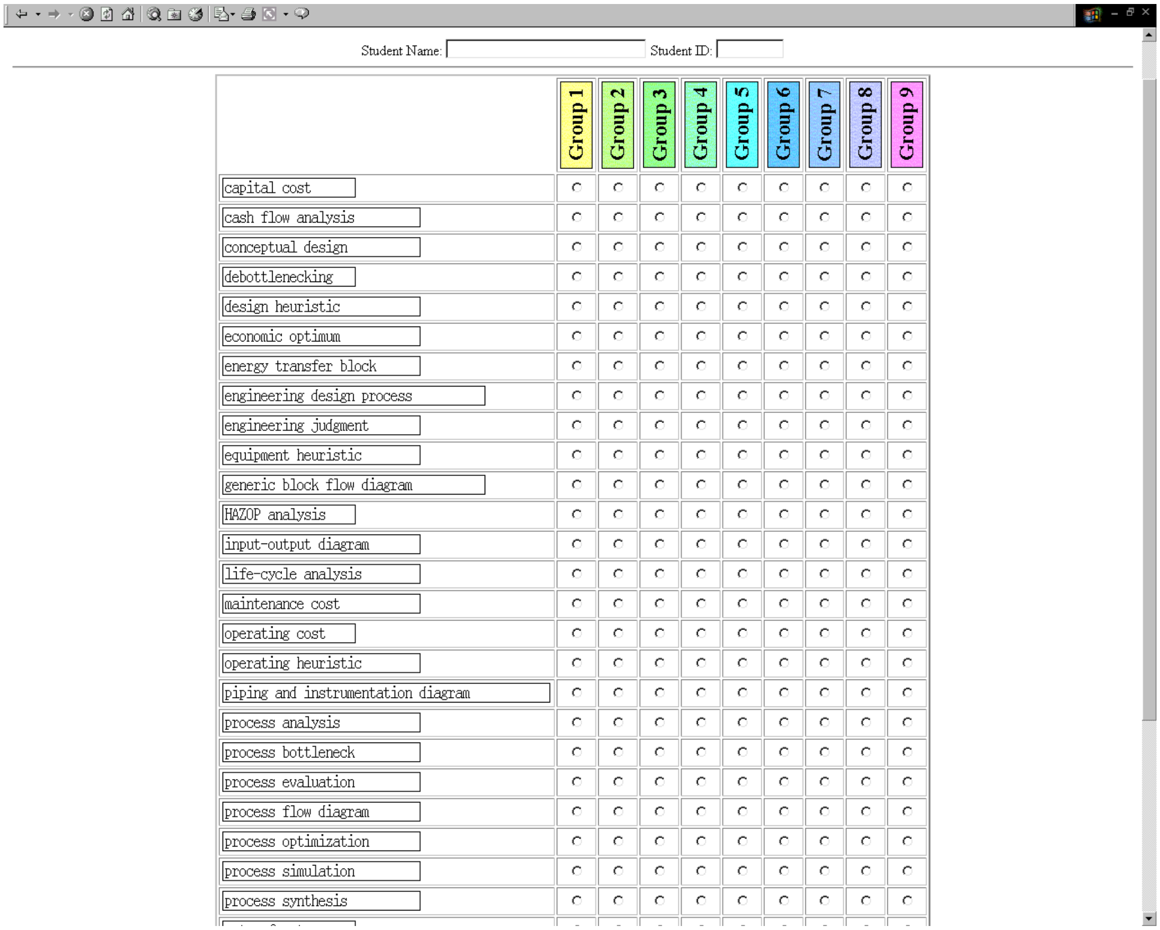

Figure 1. Screen Capture of the MDS Webpage

3) At the beginning of the semester, students were given the extra credit assignment of going to the webpage and clustering the 32 terms into logical groups. The name of each student and the date the cluster task was completed was also entered. The clustering data were collected in a PERL database. A total of 22 students completed the pretest (96% of students registered for the design course).

4) The assignment outlined in step 3 was repeated during the last week of instruction. A total of 14 students completed the posttest (61% of the students in the course).

5) The database was emailed to the investigators after the students had completed the pretest, and again after the posttest was completed.

6) These data were then input into the statistical package, SAS, and a similarity matrix was computed. This matrix was then used as the input to compute the MDS solution.

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Results

The model representing the MDS solution may be expressed from 2 to n dimensions. A statistic called "stress" gives us a goodness-of-fit measure. "Stress" can be thought of as analogous to the "residuals" in a regression solution, and therefore gives one a measure of the error in a model. The "Stress" measure for a two-dimensional solution was below 1.5 on both the pretest and posttest. This result showed that a 2-dimesional solution was adequate in both cases. The two dimensional solutions for the pretest (Figure 2) and posttest (Figure 3) are shown below.

It is customary to name the axis dimensions expressed in a MDS solution (much as one names factors in factor analysis). Based on the clustering results obtained, we labeled the x-axis "economic vs. technical" and the y-axis "process vs. product." (Refer to Table 1 for the listing of term numbers and term names.)

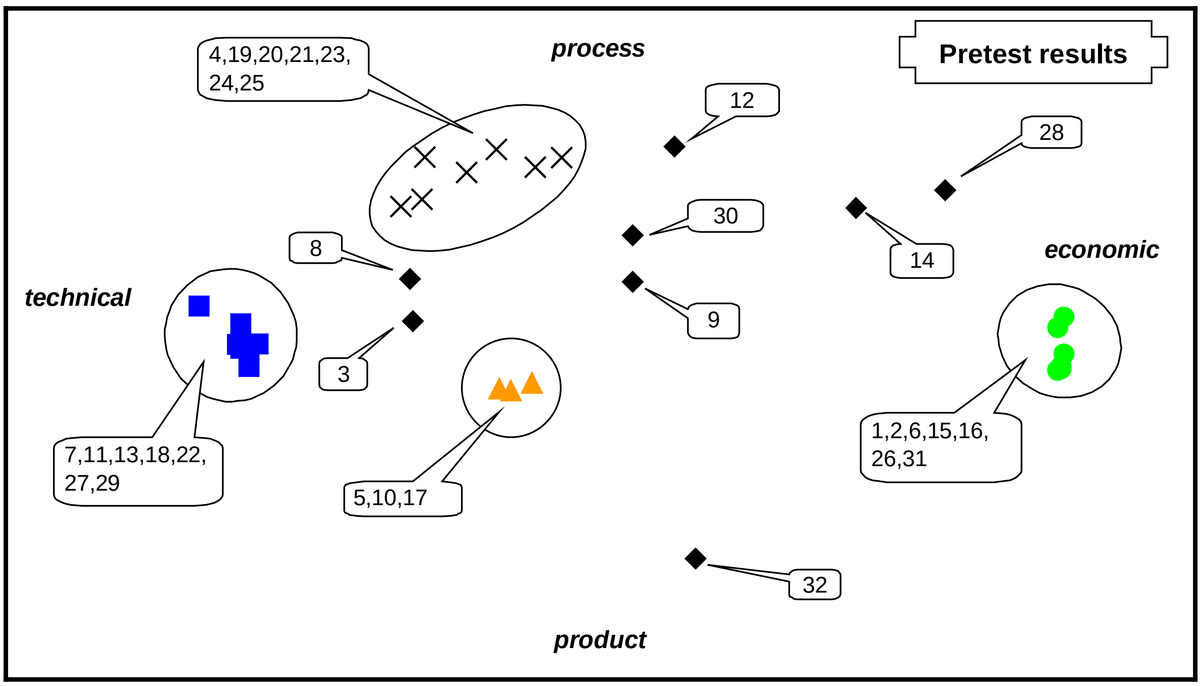

Figure 2. Pretest Results of MDS Analysis for Senior Design Terms

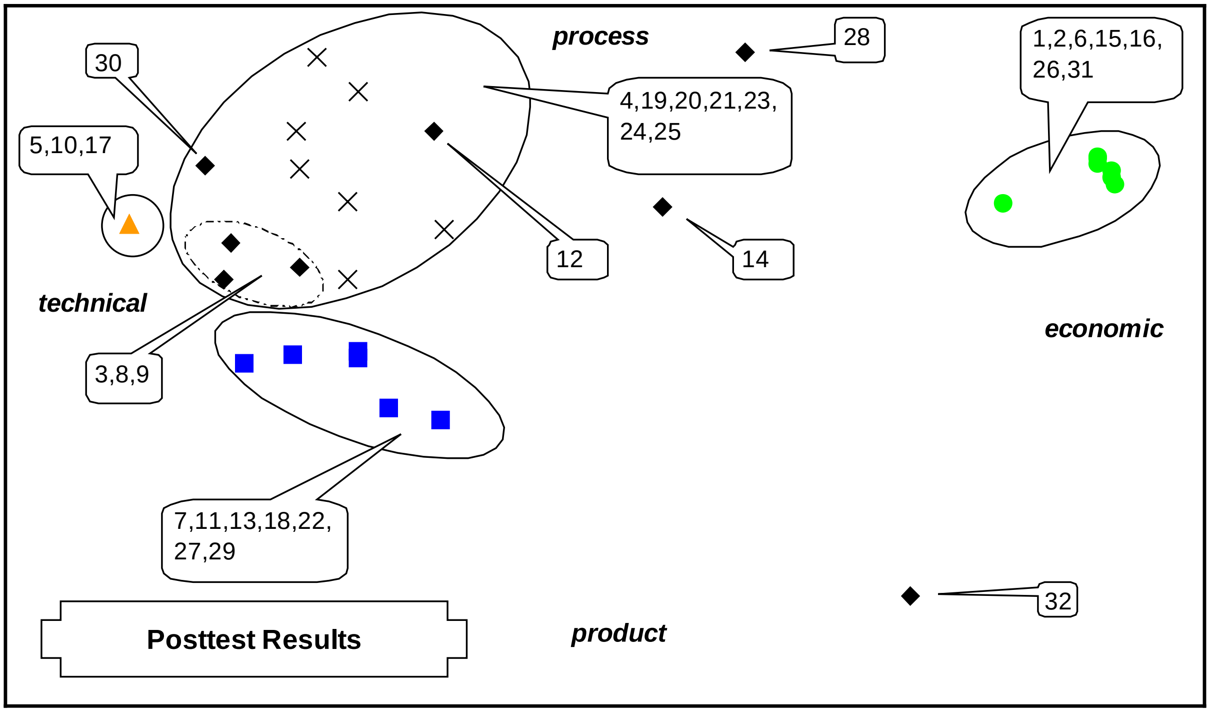

Figure 3. Posttest Results of MDS Analysis for Senior Design Terms

In the pretest (Figure 2) four distinct clusters of terms were observed:

1- A cluster containing all terms that pertained to the economic analysis of a project: capital cost (Term 1), cash flow analysis (Term 2), economic optimum (Term 6), maintenance cost (Term 15), operating cost (Term 16), rate of return (Term 26), time value of money (Term 31). We will call this grouping Cluster 1. These terms are shown in green in Figures 2 and 3.

2- A clustering listing process flow diagram terms: energy transfer block (Term 7), generic block flow diagram (Term 11), input-output diagram (Term 13), piping and instrumentation diagram (Term 18), process flow diagram (Term 22), reaction block (Term 27), separation block (Term 29). We will call this grouping Cluster 2. These terms are shown in blue in Figures 2 and 3.

3- A cluster containing terms that described analysis of processes: debottlenecking (Term 4), process analysis (Term 19), process bottleneck (Term 20), process evaluation (Term 21), process optimization (Term 23), process simulation (Term 24), process synthesis (Term 25). We will call this grouping Cluster 3. These terms are shown as gray X's in Figures 2 and 3.

4- And a cluster with three terms containing the word heuristic: design heuristic (Term 5), equipment heuristic (Term 10), operating heuristic (Term17). We will call this grouping Cluster 4. These terms are shown in orange in Figures 2 and 3.

Other terms were scattered around the plot and could not easily be placed into clusters in the pretest. These terms are: conceptual design (Term 3), engineering design process (Term 8), engineering judgment (Term 9), HAZOP analysis (Term 12), life-cycle analysis (Term 14), risk analysis (Term 28), technical optimum (Term 30) and troubleshooting (Term 32). These terms are displayed as black diamonds in Figures 2 and 3.

How does the position of these terms change in the posttest? As shown in Figure 3, Clusters 1, 2, 3, and 4 all remain in the posttest. However, some of terms are added to Cluster 3 (analysis of processes) in the posttest. The terms conceptual design (Term 3), engineering design process (Term 8), and engineering judgment (Terms 9), HAZOP analysis (Term 12) and technical optimum (Term 30) all become part of Cluster 3.

The three heuristic terms (Terms 5, 10, and 17) in Cluster 4, become so closely clustered in the posttest that they merge into a single point. However, these three points also become more closely associated with Cluster 3.

Three terms: life-cycle analysis (Term 14), risk analysis (Term 28), and troubleshooting (Term 32) continued to not be closely associated with any cluster of terms in the posttest.

Discussion

The design instructor determined that Clusters 1 and 2 were clustered accurately in both the pretest and posttest and we can infer that students have adequate understanding of the terms in these areas. Students included all terms dealing with economic analysis in Cluster 1 and indeed students in this capstone design course did have a strong background in economics having previously completed an engineering economics course. Students also are familiar with design terms and this is shown in the clustering of terms in Cluster 2.

In the pretest, Cluster 3 contained many terms which include the word “process”; however inclusion of the word “debottlenecking” in this cluster suggest that students used deeper characteristics to cluster these terms.

In the posttest, five terms were added to Cluster 3. The terms conceptual design (Term 3), engineering design process (Term 8), and engineering judgment (Terms 9) now become part of Cluster 3 suggesting that students learned the importance of conceptualizing processes using engineering judgment when designing and analyzing chemical processes. The terms HAZOP analysis (Term 12) and technical optimum (Term 30) also became part of Cluster 3 in the posttest, indicating that students in the course learned about the importance of analyzing a process for the potential of hazardous operations (HAZOP) and the importance of determining how to optimize the technical operation of a process (in addition to economic optimization).

All the words in Cluster 4 include the word "heuristic" even though the three terms are not related in a deeper, more fundamental way. It is likely that this is an example of the use of surface characteristics to group terms. We note that Cluster 4 remains intact in the posttest and in fact clusters even closer (the three terms are plotted as the exact same point). Thus the use of surface characteristics to cluster these terms becomes even stronger at the end of the semester even though the course included several lengthy discussions about the utility of heuristics to perform rapid design calculations and check detailed computer simulation results. This may indicate that even at the end of the course, students do not have a deep understanding of these terms. However, since these terms move closer to terms relating to process analysis, students have a better understanding of how design, equipment, and operating heuristics can be utilized in process analysis and design. Thus the MDS results indicate that students have some understanding of how to use the heuristics, but probably do not yet fully understand where the heuristics come from and their limitations.

Two terms, HAZOP analysis and risk analysis, should have been plotted closely together but were not in the pretest or posttest. In the posttest the term HAZOP analysis moves into Cluster 3 but is still not located near risk analysis. These results suggest that students do not yet have sufficient understanding of risk in the design and operation of hazardous chemical processes, so this topic will be emphasized more thoroughly in future offerings of the process design course.

Both pretest and posttest results also indicate that the term "life-cycle analysis" may be unclear in the students' minds. Although an important concept in terms of analyzing a chemical product from "cradle to grave," the design course does not devote much time to the life cycle of chemical species, and not surprisingly, the design students have little familiarity with the concept.

The term troubleshooting remains unclustered with any other terms in both the pretest and the posttest. Although several weeks of class time were devoted to completing process troubleshooting case studies, this result may indicate that students do not understand how this concept relates to process design and analysis.

Educational implications

The results of the MDS cluster analysis have been used to help indicate where students have accurate knowledge of engineering design (for example, when discussing the economic analysis of a design project) and where their knowledge may be incomplete (for example, when discussing life-cycle analysis, risk analysis, and troubleshooting). This information has been used to guide the development and implementation of a new module on risk assessment and HAZOP analysis in the process design course.

Based on the results of this study, we also believe MDS can be utilized as a method for identifying misconceptions students bring to the course (i.e. that different types of heuristics should be lumped into the same conceptual cluster instead of considering different types of heuristics as distinct tools for use on different design tasks). This information is now being used by the design course instructors to make more explicit the similarities, differences, and limitations of the types of design heuristics used in the course. New exercises have been developed to help students discover the origin and use of each type of heuristic.

We hope that the on-line MDS webpage will make it easier for instructors to use MDS as an assessment tool in their courses. Thus the MDS method may evolve into a kind of classroom assessment technique [6], a way of quickly gathering information about student progress which then can be used as a feedback mechanism to alter instruction and improve student understanding. We plan to use the MDS tool in future offerings of the design course to monitor the impact of the course changes mentioned above on student understanding of chemical engineering design strategies and techniques.

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RUTH A. STREVELER
Ruth A. Streveler is the Director of the Center for Engineering Education and the Director of Academic Services at the Colorado School of Mines. Dr. Streveler received her Ph.D. in Educational Psychology from the University of Hawaii at Manoa. She also holds a Master of Science in Zoology from the Ohio State University and a Bachelor of Arts in Biology from Indiana University at Bloomington.

RONALD L. MILLER
Ronald L. Miller is Professor of Chemical Engineering and Petroleum Refining at the Colorado School of Mines where he has taught chemical engineering and interdisciplinary courses and conducted research in educational methods and multiphase fluid flow for over fifteen years. He has received three university-wide teaching awards and has held a Jenni teaching fellowship at CSM. His paper entitled "Using Portfolios to Assess a ChE Program" (co-authored with Barbara Olds) won the Corcoran Award from the chemical engineering division of ASEE for best paper published in *Chemical Engineering Education* during 1999. He has received grant awards for educational research from the National Science Foundation, the U.S. Department of Education, the National Endowment for the Humanities, and the Colorado Commission on Higher Education. Dr. Miller is chair of the chemical engineering department assessment committee and chair of the CSM assessment committee.