TEACHING CREATIVE PROBLEM-SOLVING SKILLS IN ENGINEERING DESIGN

J.G. MACKENZIE, R.M. ALLEN,* W.B. EARL, I.A. GILMOUR
University of Canterbury • Christchurch, New Zealand

Problem solving is an activity that engineers are engaged in every day, but not many professional engineers are taught problem-solving strategies as part of their undergraduate education. In the literature, some writers[1-3] have been particularly concerned with problems based on mathematics and logic, whereas others[4-8] have been more concerned with open-ended problems and lateral thinking.

Some research on problem solving has been based on computer-aided modeling of mental processes known as artificial intelligence (AI).[9-11] Other work has been based on problem-solving experiments with human subjects[12] and studies of thinking.[13] Much of the research, however, has been concerned with logical confusion and errors; little research to date has been done on the teaching of problem-solving skills in higher education.

The teaching of problem-solving skills to undergraduate engineering students has been described.[14-17] From an industrial point of view,[18] problem solving is a crucial skill for engineers in manufacturing. The time to teach this skill is critical in the professional development of an engineer and may be best immediately following graduation when the engineer is confronted with what seems to be an unsolvable problem.

Our view is that there is a balance between teaching problem-solving skills early in the undergraduate degree course so the skills can be used in the educational process, and teaching these skills later when students have the maturity to appreciate their benefits and the experience to apply the techniques. We have chosen to present problem-solving techniques in the third year of a four-year degree program.

A NEW APPROACH TO ENGINEERING DESIGN

In traditional design teaching, the design process is often broken into a number of incremental steps: defining the task, goal setting, establishing a concept, defining the constraints, setting the specifications, listing the alternatives, evaluating and selecting the best alternatives, formulating an appropriate mathematical model, calculating, modifying, costing, drawing, constructing, testing, and finally, commissioning. A general structure of the design process, once recognized and defined, is then adapted as a design strategy for future projects. While the approach of retrospectively studying successful design projects, recognizing the various areas of activities and their logical sequence, and applying it to new projects works well, it relies heavily on experience for a successful outcome. It is exactly this experience in application, however, that our undergraduate students lack. A practical design strategy is more appropriate for novice engineers.

Design has been taught to our chemical engineering undergraduates for many years by a traditional case-studies approach that involved dissecting the design process into its various elements, imparting relevant knowledge by formal

Judith Mackenzie *is Senior Tutor in the School of Engineering, University of Canterbury. She has a Master's degree in Education and has recently completed a PhD in Chemical and Process Engineering. Her teaching and research focuses on the application of computers as a tool for innovative teaching in chemical engineering education.*
Maurice Allen *is Associate Professor in the Department of Instrumentation and Control Engineering at Murdoch University. His teaching and research centers on process control, the modeling and simulation of industrial processes, and the application of computing to process engineering and teaching.*
Brian Earl *is Associate Professor of Chemical and Process Engineering, University of Canterbury. His teaching interests are in process design, corrosion, and electrochemical engineering, and his research interests are in expert systems in process design, chemical engineering education, corrosion, and alternative transport fuels. Dr. Earl is currently on leave at Cornell University*
Ian Gilmour *is Senior Lecturer in the Department of Chemical and Process Engineering, University of Canterbury. His teaching interests are the design of process equipment, heat exchangers, combustion of fuels and energy, and material balances for chemical processes. His research interests are the efficient uses of fuels and energy in the process industry, extraction of nutraceuticals from agricultural and forest residuals, and computer modeling for the pulp and paper industry.*

* *Address: Instrumentation and Control Engineering, Murdoch University, Western Australia 6168*

lectures, and demonstrating how experienced engineers have designed successful systems. It was hoped that this approach would imbue the students with sufficient knowledge and skills to become novice designers.

These efforts to teach design led to the realization that competence in design seemed to be achieved by a handful of students who rose to the challenge and were able to apply skills, knowledge, and other personal attributes, often with outstanding results. The recipe for success seemed to combine such ingredients as organization, lateral thinking, computation, practical experience in workshop skills, and an ability to think in abstract terms. These special talents, which every student possesses, need to be developed and honed to a sharper edge.

> ***. . . there is a balance between teaching problem-solving skills early in the undergraduate degree course so the skills can be used in the educational process, and teaching these skills later when students have the maturity to appreciate their benefits.***

In recent years, we have adopted a problem-solving approach similar to that of Woods[19] for teaching third-year engineering design. This design course embraces a wide spectrum of engineering topics: mixing and pumping of liquids, flowsheeting, column design, pinch technology, process reliability, separation processes, and properties of engineering materials. A problem-solving foundation to engineering design provides students with the necessary skills and confidence to be able to tackle any problem, design or otherwise, without feeling hindered by lack of direct experience in the particular topic.

CREATIVE PROBLEM-SOLVING MODULES

Students learn best when they directly experiment with subject matter and are actively involved with the material.[20] Interactive computer instruction provides such active learning and allows students to "review and demonstrate mastery of the material at his/her own pace, [and] provides them with immediate feedback to their responses."[21]

Interactive computer-based learning depends on software that is easy to use, maintains a focus on the concepts, has minimal tediousness, promotes learning, and gives individual guidance. *Strategies for Creative Problem Solving*[15] is a collection of interactive computer modules and is used to supplement problem-solving lectures. Additional features in some modules, such as the use of graphical animation and entertaining motivators, were included to increase student interest in, and motivation for, the module content.[22]

The content of each module is

1. An Introduction to Problem Solving

This module provides the user with the motivation to use creative problem-solving strategies. Topics include the characteristics of effective problem solvers, fear of failure, the need for risk-taking, paradigm shifts, having a vision, a problem-solving heuristic, creative thinking, and working in teams. The introduction presents the topics as well as their application to a contamination problem in a municipal water-supply system.

2. Problem Statement Definition Techniques

The goal of this module is to help the user properly define the problem. Several techniques are used to better define the problem statement: for example, the Dunker Diagram,[19] the McMaster Five-Point Strategy,[19] the Present-State Desired-State technique,[23] and the Statement-Restatement technique. The user reviews the methods of problem definition in two examples: problems at a flashlight manufacturing plant are analyzed with the McMaster Five-Point Strategy and a second example involves a grocery store freezer door fogging up and blocking the customer's view of the contents.

3. Brainstorming: Methods of Solution Generation

This module helps the user generate original yet applicable solutions to a specific problem through brainstorming. The review section introduces the basic techniques and ideas for improvement, including Osborn's checklist,[24] random-word stimulation, futuring, conceptual blockbusting, and using other people's views.

These methods are illustrated through specific examples. To test the techniques, the user is first asked to brainstorm a list of synonyms for the word "money." Once the user is finished, the user's list is compared to one generated by a group of college students. Second, the user selects at least two brainstorming topics chosen from a list of five possible scenarios, ranging from encouraging recycling in a community to preventing zebra mussel infestations on power-plant water-intake pipes. For each scenario, a detailed problem statement is given as well as a few example solutions to get the user started.

4. Potential-Problem Analysis: Avoiding Future Problems

Potential problems should be anticipated and analyzed before they happen. Three parts of potential problem analysis (possible causes, preventative action, contingent actions) are explained in the introduction. The user then has a choice of scenarios (either a cross-country road trip or preparation for an interview) that are used to review the techniques. The main scenario is based on the 1993 world solar-car race, Sunrayce'93.[25] The background of the race is presented with additional explanation of relevant technology, including the solar-cell mechanism and the importance of gear ratios in power-train design. A potential-problem analysis chart for the event is prepared by the user to determine problems that might occur during a race and their prevention.

5. Planning: Implementation of Solutions

Gantt charts,[26] critical-path analysis,[27] deployment charts, and budget proposals are introduced as tools that aid planning. These four techniques are illustrated in two introductory scenarios: planning the ergonomic design of an office and planning a student conference. In the interactive section of the module, the user is part of a team participating in a student competition to build a one-tenth-scale model of a steel bridge. Each of the planning techniques is then applied to generate a Gantt chart, a critical-path chart, a deployment chart, and a budget for the project.

6. Evaluation: Solution Evaluation Techniques

The importance of continually re-evaluating a solution throughout the course of a project is emphasized. The technique presented is the evaluation checklist, illustrated by the near disaster of marketing the new Coca Cola. The example demonstrates the use of an evaluation checklist to prevent millions of dollars from being wasted. In the interactive scenario, the user is presented with the problem of a paper mill that plans to expand its production capacity. The user is given the opportunity to talk to other virtual employees in the company and to gather the necessary information to evaluate the proposed expansion. Findings are submitted to the project supervisor for immediate feedback.

COURSE ORGANIZATION, ASSESSMENT, AND EVALUATION

The problem-solving section of the design course consisted of nine one-hour lectures, six hours of laboratory sessions (with about the same amount of time devoted to working through set problems), and the computer problem-solving modules. This allocation of time was just sufficient to introduce the forty third-year students to the basic concepts, give them the experience of applying these new skills, and expand their confidence in analyzing and solving new problems independently.

We emphasized the importance of communication and working in teams in the process of problem solving. We also used the technique of attacking problems,[28] with one of a pair playing the role of problem solver and the other the listener, and then alternating roles. The first problem-solving assignment, worth 10%, gave randomly selected student pairs the opportunity to apply this technique to a set of problems taken from the McMaster problem-solving program.[19] The second assignment was based on the Fogler interactive computer modules and was also worth 10%. Each pair of students was assigned two of the computer modules to complete each week for three weeks—six modules in total. At the completion of each module, a computer-generated performance score was recorded by students and handed in as part of their assessment. Students were given the option of repeating the modules as often as they wished to improve their score—and some did, with their best score being credited. A questionnaire completed by students at the end of the design course provided an evaluation of Whimbey pairs[28] and the computer problem-solving modules.

RESULTS AND DISCUSSION

The distribution of marks in the first assignment was high, with a skew toward a possible score of ten. When working through the

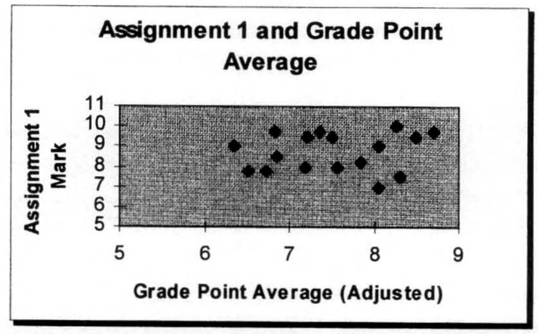

Figure 1. Marks on Assignment 1 compared with adjusted grade point average.

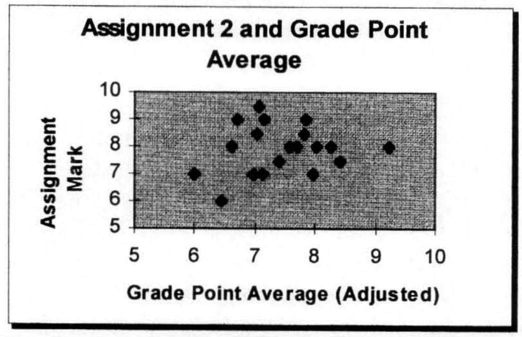

Figure 2. Marks on Assignment 2 compared with adjusted grade point average.

TABLE 1
Student Comments on Whimbey's Method

Problem Solver
- As the problem solver, I found that when solving problems, I tend to like to put things into mathematical equations.
- For the basic problem, I did write out more than I usually would. It was fun and I would like to do more of it.
- I think I work too much out in my head and tend to rush to give an answer.
- I tend to attack problems head on, noting down all the information supplied as I read it through.
- I enjoyed solving these problems.
- The help of a listener was very useful; their ideas and reasoning are often very different and it's good to compare and see their point of view.

Listener
- In problem solving you must read the question carefully, jot down any conditions, and then determine what the problem is asking you to solve.
- The hardest thing was not to get carried away and tell the problem solver the answer when I knew it.
- It was a much easier task to be the listener than the solver.
- It's good to try to show the other person a different way of thinking.
- Being the listener is not an easy task!
- Listening is generally not too hard—often the solver doesn't vocalize everything.

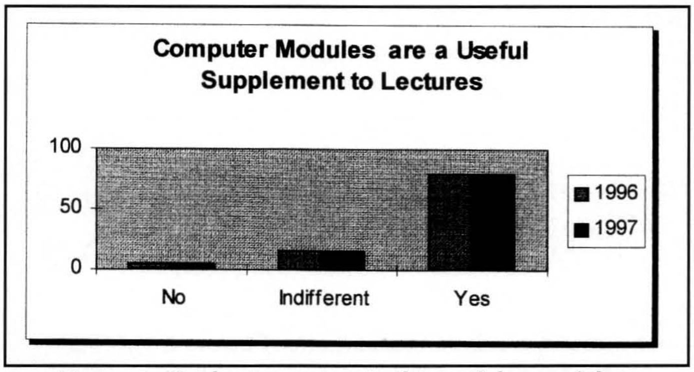

Figure 3. Student response to the usefulness of the interactive computer modules.

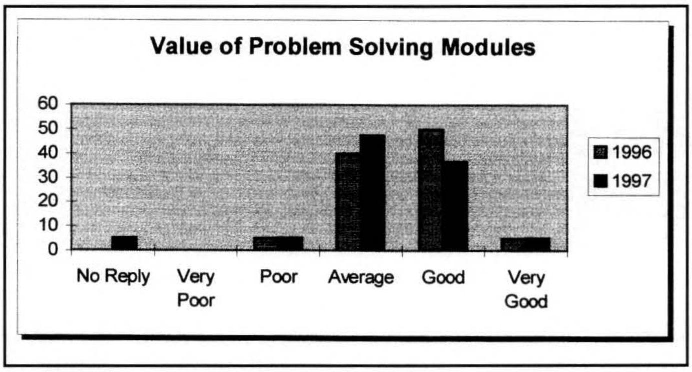

Figure 4. Students opinion of the value of the interactive problem-solving modules.

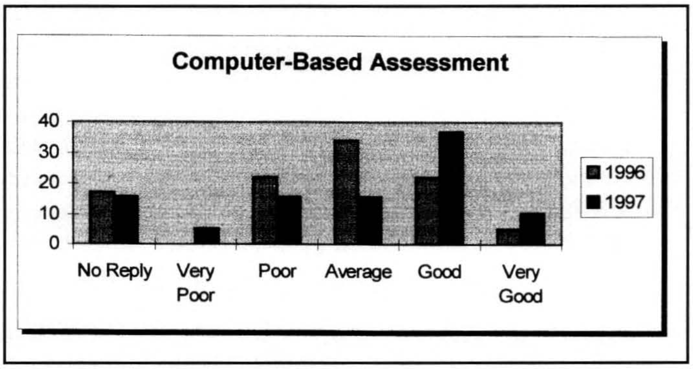

Figure 5. Student response to computer-based assessment.

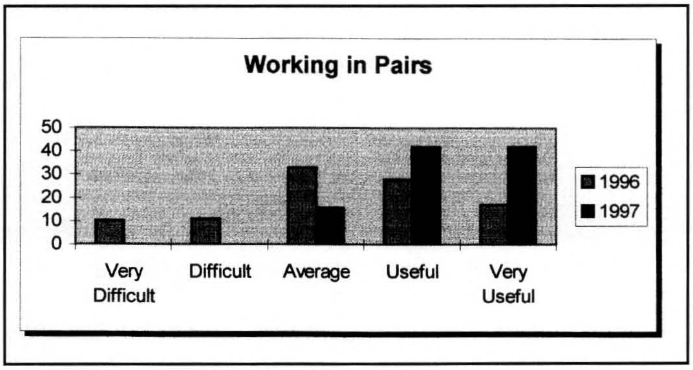

Figure 6. Student response to working in pairs.

McMaster problem set, a number of students showed enthusiasm for the Whimbey pair concept, obtaining full marks. Table 1 has a sample of student comments taken from the questionnaire.

The assessment mark for each pair for two problem-solving assignments has been compared with the group-adjusted grade point average for the 1996 end-of-year examinations in Figures 1 and 2.

The grade point average (GPA) for each student is the average grade for all papers in the 1996 examinations and reflects the students' final academic achievement. The GPA is assigned a numerical equivalent ranging from 9 for an A+ to 2 for a C. The adjusted grade point average (GPAJ) was recalculated to align means and standard deviation with marks out of 10.

Statistical analysis showed no significant relationship between problem-solving performance and previous academic results for the two problem-solving assignments. A reason for the results is that problem solving is a different skill from conventional academic performance. Additionally, the results can be explained by differences in testing procedures. The problem-solving assignments were power assessments, without direct time constraints, whereas examinations were speed tests, with stringent time restrictions to the examination time.

Student responses to the questionnaire on the usefulness of the computer modules, their rating of the interactive problem solving modules, their opinion of computer-based assessment and working in pairs are shown in Figures 3 through 6.

Figure 3 shows that 78% of students in 1996 and 1997 found the computer modules to be a useful supplement to lectures, while 10% were indifferent and 2% did not find them useful.

In Figure 4, student rating of the interactive problem-solving modules indicated a positive response, with fewer than 5% (1996) and fewer than 10% (1997) rating them as worse than average. Students responded well to the practical problems in the computer modules, helping to understand different problem-solving techniques.

Computer-based assessment was introduced to the students in 1996. Figure 5 shows that 61% (1996) and 63% (1997) of the students found this form of assessment very good, good, or average; 17% of the students (1996) did not respond to this question.

The interactive computer modules provided a new and different environment for learning that students found to be a useful supplement to lectures. Working in pairs for Assignments 1 and 2 enabled students to help each other with problem solving. Most of the students supported working in pairs for Assignment 2, as shown in Figure 6; 78% of the

Continued on page 157.

Problem-Solving Skills

Continued from page 153.

students found it to be very useful, useful, or average. Sharing ideas and discussing them were understood to be valuable problem-solving techniques. The main disadvantage for students was having to plan time to work together. In 1997, student opinion of the problem-solving modules improved significantly, as shown in Figures 3 through 6.

ASSESSMENT OF EACH MODULE

Each module was assessed and marks recorded on-line. Tables 2 and 3 show the mean and standard deviation of student assessment for each computer module. In 1996, all students scored full marks on the introduction module, whereas this module ranked fourth in 1997. Planning and brainstorming ranked the lowest for both 1996 and 1997. We believe that students lack the necessary experience in these skills that are developed later in the workforce.

TABLE 2
Student Assessment of Each Computer Module, 1996

	Mean	Standard Deviation
• Introduction	1.00	0.01
• Potential Problems	0.98	0.06
• Evaluation	0.89	0.17
• Define	0.86	0.15
• Planning	0.68	0.21
• Brainstorming	0.41	0.25

TABLE 3
Student Assessment of Each Computer Module, 1997

	Mean	Standard Deviation
• Define	0.92	0.10
• Evaluation	0.87	0.21
• Potential Problems	0.86	0.09
• Introduction	0.83	0.11
• Brainstorming	0.65	0.27
• Planning	0.64	0.07

CONCLUSION

The development of problem-solving skills is an integrated part of the teaching of design at the third-year level of our chemical and process engineering degree course. Students appreciated the problem-solving approach to assignments. Working in pairs for problem solving was found to be beneficial by most of the students, although arranging a suitable time to work together was a disadvantage.

Problem solving is a skill that can be learned. It is imperative that our graduates have the necessary skills and strategies to deal confidently with new situations and problems encountered in their professional careers.

REFERENCES

1. Wickelgren, W.A., *How to Solve Problems,* Freeman, San Francisco, CA (1974)
2. Polya, G., *How To Solve It,* Doubleday, New York, NY (1957)
3. Polya, G., *Mathematical Discovery, Vol. 1: On Understanding, Learning, and Teaching Problem Solving,* John Wiley, New York, NY (1962)
4. De Bono, E., *The Use of Lateral Thinking,* Penguin, Harmondsworth (1967)
5. De Bono, E., *The Five-Day Course in Thinking,* Penguin, Harmondsworth (1968)
6. De Bono, E., *The Mechanism of Mind,* Penguin, Harmondsworth (1969)
7. De Bono, E., *PO: Beyond Yes and No,* Revised Edition, Penguin, Harmondsworth (1973)
8. Wertheimer, M., *Productive Thinking,* Tavistock, London (1961)
9. Johnson-Laird, P.N., and P.C. Watson, eds., *Thinking: Readings in Cognitive Science,* Cambridge University Press, Cambridge (1977)
10. Newell, A., and H.A. Simon, *Human Problem Solving,* Prentice-Hall, Englewood Cliffs, NJ (1972)
11. Kahney, H., *Problem Solving: A Cognitive Approach,* Open University Press, Milton Keynes (1986)
12. Johnson-Laird, P.N., *Mental Models,* Cambridge University Press, Cambridge (1983)
13. Wittrock, M.C., "Students' Thought Processes," in *Handbook of Research in Teaching,* M.C. Wittrock, ed., Macmillan, New York, NY; (1986)
14. Woods, D.R., *The McMaster Problem Solving (MPS) Program,* Chemical Engineering Department, McMaster University, Ontario, Canada (1985)
15. Fogler, H.S.L., S.E. LeBlanc, and S.M. Montgomery, *Strategies for Creative Problem Solving,* University of Michigan, Ann Arbor, MI (1995)
16. Ko, E.I., and J.R. Hayes, "Teaching Awareness of Problem-Solving Skills to Engineering Freshmen," *J. of Eng. Ed.,* October (1994)
17. Allen, R.M., I.A. Gilmour, and J.G. Mackenzie, "Creative Problem Solving," Proceedings of 24th Australian and New Zealand Chemical Engineering Conference and Exhibition, **4**, Sydney, Australia, (1996)
18. Maul, G.P., and J.S. Gillard, "Teaching Problem Solving Skills," *Computers and Ind. Eng.,* **31**(1/2) (1996)
19. Woods, D.R., "A Strategy for Problem Solving," Course Notes, McMaster University, Ontario, Canada (1983)
20. Felder, R.M., "Teaching and Learning Styles in Engineering Education," *Eng. Ed.,* April (1988)
21. Fogler, H.S., S.M. Montgomery, and R.P. Zipp, *Computer Applications in Engineering Education,* **1**(1), September/October (1992)
22. Snow, R., and M. Farr, *Aptitude, Learning and Instruction, Vol. 3: Cognitive and Affective Process Analysis,* Erlbaum, Hillsdale, NJ (1987)
23. Higgins, J.S., *et al.,* "Identifying and Solving Problems in Engineering Design," *Studies in Higher Education,* **14**(2) (1967)
24. Adams, J.L., *Conceptual Blockbusting: A Guide to Better Ideas,* W.H. Freeman and Co., San Francisco, CA (1974)
25. Morrison, D., *University of Minnesota Solar Vehicle Project,* June 11 (1993)
26. Gantt, H.L., *Work, Wages and Profits,* New York, NY (1910)
27. Lockyer, K.G., "Critical Path Analysis," *Accountants Digest,* No. 4, Institute of Chartered Accountants in England and Wales, London (1991)
28. Whimbey, A., and J. Lochhead, *Problem Solving and Comprehension: A Short Course in Analytical Reasoning,* Franklin Press, Philadelphia, PA (1980) ❐