Int. J. Engng Ed. Vol. 24, No. 3, pp. 558–566, 2008
Printed in Great Britain.

0949-149X/91 $3.00+0.00

Enhancing Student Learning of an Undergraduate Manufacturing Course with Computer Simulations*

NING FANG AND GARY A. STEWARDSON
Department of Engineering and Technology Education, College of Engineering, Utah State University, Logan, UT 84322, USA. Email: nfang@engineering.usu.edu

MARGARET M. LUBKE
Research and Evaluation Methodology Unit, College of Education and Human Services, Utah State University, Logan, UT 84322, USA

Computer-assisted instruction is an innovative instructional strategy that has been receiving increasing attention in engineering and technology education. This paper describes our recent efforts to develop and implement a computer simulation program to enhance student learning of a manufacturing course. Examples of student work assignments that demonstrate our instructional strategy are included. Student learning outcomes were evaluated by using a Likert-type and open-ended questionnaire to survey students' attitudes and experiences toward our computer simulation program, and by developing a unique mechanism that includes technical questions at varying degrees of difficulty to investigate if our computer simulation program helps enhance student learning.

Keywords: computer simulations; instructional strategy; learning assessments; manufacturing

INTRODUCTION

Computer simulations as a new tool to assist in teaching and learning

COMPUTER-ASSISTED INSTRUCTION, enabled by rapid development and breakthroughs in computer science and technology, has received increasing attention in recent years [1]. Computer-assisted instruction has many advantages over traditional classroom lectures, including providing students with rapid inquiry-based learning experiences, allowing students to perform computer experiments at their own pace and within their own schedule and, more importantly, enabling students to receive immediate feedback and to 'see' the results of their experiments rather than to 'hear' about the results during an instructor's lecture.

Computer-assisted instruction is used in various ways including computer simulations [2–7], virtual reality [8–9], multi-media instruction [10–12], and on-line distance education [13–14], to name a few. Among these, computer simulations have been widely employed in many disciplines of engineering and technology education. For example, in chemical engineering education, Clark and DiBiasio [15] employed computer simulations to present hands-on experiences showing students the potential solutions to the differential equations that govern flow, heat transfer, mass transfer and chemical reactions within material processing equipment. In manufacturing engineering, Rosentrater and Visser [16] employed computer software to simulate injection molding processes and taught students the Design of Experiments method of manufacturing as well as how to use statistical procedures in this situation. In mechanical engineering, Sheyman [17] used computer simulations in a thermodynamics laboratory to help students become familiar with the set up before working in hands-on laboratories.

Two factors significantly impact the learning outcomes of computer simulations: 1) the availability and the quality of an appropriate computer simulation program; 2) the strategy of how the program is implemented in laboratory instruction. A poorly designed computer simulation program and/or an inappropriate strategy in student laboratory assignments do nothing but obstruct student learning.

Instructional goals of our machining course

In an effort to enhance our educational program in manufacturing engineering, we recently initiated a plan that aims to enhance student learning in manufacturing courses by developing and implementing a computer simulation program that addresses the two factors described above. The plan, which is sponsored by the Course, Curriculum, and Laboratory Improvement program of the National Science Foundation, focuses on an

* Accepted 17 December 2007.

upper-division undergraduate manufacturing course that we teach: Metal Machining. We selected this course because machining is one of the most common and accessible manufacturing processes to which many engineering students are exposed. Machining is taught in numerous universities and colleges either as a stand-alone course or as an integral component of a manufacturing course. In addition, it is taught not only in mechanical, industrial, and manufacturing engineering programs, but also in many applied manufacturing technology programs.

We offer the machining course to senior level undergraduate students in the mechanical engineering department. The course covers nearly all important aspects in metal machining, including topics on:

- Metal Cutting Operations and Terminology;
- Essential Features of Metal Cutting;
- Forces and Stresses in Metal Cutting;
- Heat in Metal Cutting;
- Cutting Tool Materials;
- Machinability;
- Coolants and Lubricants; and
- High-Speed Machining.

To have students master fundamental machining concepts and theories, we developed five instructional goals for the course. At the end of the course, students should be able to demonstrate ability to:

1. Identify correct tool geometry and their effects;
2. Calculate and experimentally measure the shear-plane angle;
3. Perform fundamental analysis on the cutting forces and temperatures in machining;
4. Understand different tool material properties and tool-wear mechanisms and apply Taylor's tool-life equation to predict tool life; and
5. Analyze factors affecting the machined surface quality.

Our instructional strategy

To accommodate different learning styles of students [18–20], we designed a diversified instructional strategy that consisted of classroom lectures, industrial professionals guest speakers, real-world manufacturing laboratory experiments, and computer simulation projects.

The overall goal of computer simulation projects is to have students develop a fundamental understanding of the complex relationships among various machining variables and as well as improving their problem-solving skills. This goal represents a continuum of understanding from novice to expert typically developed only after years of experience. It is believed that through the use of computer simulations, students would be moving along their continuum more rapidly towards a higher level of experience [1].

A total of six computer simulation projects were designed for students to conduct throughout the semester. These projects involve the use of a computer program that we developed through years of machining research efforts. Each project corresponds to one or two of the instructional goals described before. We first gave students a brief introduction on how to use our computer simulation program and described the detailed requirements of the simulation project. Students then performed their simulations in a computer laboratory and submitted their written project report for evaluation. In several of the simulation projects, we also required students to perform real-world experiments in a manufacturing laboratory to obtain essential data to input into the computer simulation program.

The structure and contents of this paper

This paper begins by briefly describing the mathematical model of machining that we used to develop the computer simulation program and goes on to describe how our computer simulation program was implemented, including examples of student work assignments. Finally, it presents our method of evaluating student learning outcomes, including: 1) using a Likert-type and open-ended questionnaire to survey students' attitudes and experiences toward our computer simulation program, and 2) developing a unique mechanism, which includes a set of technical questions at varying degrees of difficulty, to investigate if computer simulations help enhance student learning.

DEVELOPMENT OF A COMPUTER SIMULATION PROGRAM FOR METAL MACHINING

Overall framework of the learning modules

Our computer simulation program includes three interactive learning modules. Each module covers a major aspect of machining. These three modules include the following.

1. *Learning Module A: Cutting Forces, Temperatures, and Chip Formation*. Students learn how the cutting conditions, tool geometry, tool–chip friction, and work materials affect the cutting forces, the cutting temperatures, and chip formation in metal machining.
2. *Learning Module B: Tool Wear and Tool Life*. Students learn how the cutting conditions, tool materials, and work materials affect tool wear and tool life.
3. *Learning Module C: Machined Surface Roughness and Residual Stress*. Students learn how the cutting conditions and tool geometry affect the machined surface roughness and residual stress.

Uniqueness of the learning modules

The above learning modules are unique in two aspects. First, they provide rapid response to the change of input parameters, enabling 'real-time' predictions of machining parameters. The mathematical model of machining that we employed in the development of the learning modules was either an analytical model (for Module A) or empirical models (for Modules B and C), rather than a traditionally-used, time-consuming finite-element model. When making changes of input parameters, students can instantly see the prediction results. This rapid-response feature is very important and enables students to obtain immediate feedback on their learning outcomes.

Second, our learning modules all have user-friendly interface designs. It takes no more than 20 minutes to explain to students how to use these modules and run computer simulations.

Mathematical model of machining and its experimental validation

Based on years of active research on metal machining, we developed an analytical model of chip formation for metal machining [21]. This model was used to develop the computer simulation program (Module A) and is briefly described in the following paragraphs. Interested readers can refer to our papers [21–23] for all technical details of the model.

Figure 1 shows our analytical slip-line model of chip formation for machining. The size of shear zones shown in Fig. 1 are exaggerated in order to show slip-lines clearly within these zones. The rounded tool edge *BN* is approximately represented by two straight chords *SB* and *SN*. Point

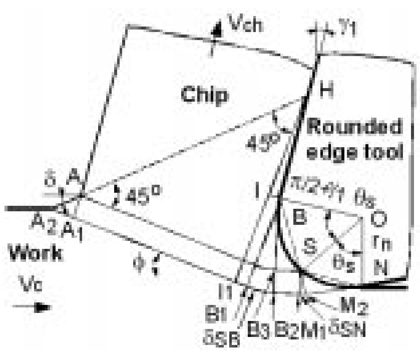

Fig. 1. The analytical model of chip formation for metal machining [21].

S is a stagnation point of material flow. Part of the material flows upwards from point *S* to point *B* along the rounded tool edge, while the other part of the material flows downwards from point *S* to point *N*.

Because the slip-line $A_2A_1I_1B_1B_2M_1M_2N$ consists of several straight and curved segments, the commonly known 'shear-plane' angle ϕ remains constant only along the straight segment $A_2A_1I_1B_1$. Other important variables shown in Fig. 1 include the chip flow velocity V_{ch}, the tool rake angle γ_1, the tool edge radius r_n, and the angle θ_s that determines the position of the stagnation point *S* on the rounded tool edge.

The chip thickness h_{ch} is calculated as

$$h_{ch} = SB \cdot cos\zeta_{SB} + \frac{BH}{2} \cdot \left[1 + \sqrt{1 + (\frac{\tau_{rake}}{k})^2} + \frac{\tau_{rake}}{k}\right] \quad (1)$$

where τ_{rake} is the tool–chip frictional shear stress on the tool rake face; *k* is the average material shear flow stress; and *SB*, *BH*, and ζ_{SB} are calculated as

$$SB = 2 \cdot r_n \cdot sin\left(\frac{\pi}{4} + \frac{\gamma_1}{2} - \frac{\theta_s}{2}\right) \quad (2)$$

$$BH = \frac{h_c + \sqrt{2} \cdot (\Delta S + SB \cdot cos\zeta_{SB}) \cdot sin\delta - r_n \cdot (1 + sin\gamma_1)}{(cos\zeta_{rake} + sin\zeta_{rake}) \cdot sin(\gamma_1 + \zeta_{rake})} \quad (3)$$

$$\zeta_{SB} = [cos^{-1}(\tau_{SB}/k)]/2 \quad (4)$$

where τ_{SB} and τ_{SN} are tool–chip frictional shear stress above and below, respectively, the stagnation point on the cutting edge. If the forces across $A_2A_1I_1B_1$, B_1B_2, B_2M_1, M_1M_2, M_2N are denoted by $\vec{F}_1$, $\vec{F}_2$, $\vec{F}_3$, $\vec{F}_4$ and $\vec{F}_5$, then the resultant force $\vec{F}$ is

$$\frac{\vec{F}}{kh_cw} = \frac{\vec{F}_1}{kh_cw} + \frac{\vec{F}_2}{kh_cw} + \frac{\vec{F}_3}{kh_cw} + \frac{\vec{F}_4}{kh_cw} + \frac{\vec{F}_5}{kh_cw} \quad (5)$$

where *w* is the width of cut. The material flow stress *k* is predicted from the well-known Johnson–

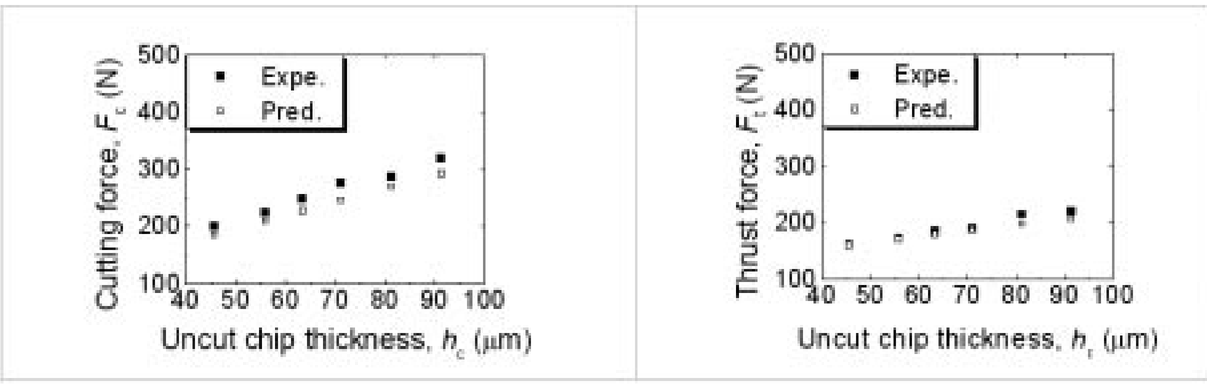

Fig. 2. Example of experimental validations of the model [22].

Cook constitutive model, which involves the determination of the average strain, strain rate, and temperature in the primary shear zone.

The above model has been experimentally validated on a variety of work materials and under a wide range of cutting conditions and tool geometry [22, 23]. Figure 2 shows one example of experimental validations. As seen from Fig. 2, the predicted cutting force F_c and thrust force F_t are in excellent agreement with their experimental values.

IMPLEMENTATION OF THE COMPUTER SIMULATION PROGRAM

Student work assignments

Six computer simulation projects were designed and assigned to students throughout the semester. Table 1 shows these projects, associated learning modules, and instructional goals.

An example of student work assignments

Take Project #1 as an example to explain how students learned fundamental machining concepts and theories through computer simulations. In Project #1, students performed three computer simulations (called Simulation Groups A, B, C, respectively) using Learning Module A of the computer simulation program.

Simulation Group A: Students learn how the cutting speed affects the shear-plane angle

- Step 1: Select five different values for the cutting speed, while keeping all the other inputs (such as the feed rate, tool rake angle, tool–chip friction, and work materials) constant.
- Step 2: Run the computer program to predict the shear-plane angle for each selected cutting speed. Save the predicted shear-plane angles into an Excel file for post-processing.
- Step 3: Use Excel to plot a figure showing the relationship between the cutting speed and the shear-plane angle.
- Step 4: Draw a conclusion about how the cutting speed affects the shear-plane angle.

Simulation Group B: Students learn how the tool rake angle affects the shear-plane angle

- Step 1: Select five different values for the tool rake angle, while keeping all the other inputs constant.
- Step 2: Run the computer program to predict the shear-plane angle for each selected tool rake angle. Save the predicted shear-plane angles into an Excel file for post-processing.
- Step 3: Use Excel to plot a figure showing the relationship between the tool rake angle and the shear-plane angle.
- Step 4: Draw a conclusion about how the tool rake angle affect the shear-plane angle.

Simulation Group C: Students learn how the tool–chip friction affects the shear-plane angle

- Step 1: Select five different values for the tool–chip friction, while keeping all the other inputs constant.
- Step 2: Run the computer program to predict the shear-plane angle for each selected tool–chip friction. Save the predicted shear-plane angles into an Excel file for post-processing.
- Step 3: Use Excel to plot a figure showing the relationship between the tool–chip friction and the shear-plane angle.
- Step 4: Draw a conclusion about how the tool–chip friction affect the shear-plane angle.

For brevity, only one example of a student's work performed in Simulation Group C is shown here. In this example, a student chose seven different values (instead of the five values requested) for the

Table 1. Student work assignments

Computer simulation project	Learning module	Instructional goal
Project #1: How the cutting conditions, tool geometry, and tool–chip friction affect the shear-plane angle.	Module A	Goals 1 and 2
Project #2: How the cutting conditions, tool geometry, and work materials affect the cutting forces.	Module A	Goals 1 and 3
Project #3: How does the feed rate affect the tool–chip friction and the chip thickness?	Module A	Goal 3
Project #4: How the cutting conditions, tool geometry, and work materials affect the cutting temperature.	Module A	Goal 3
Project #5: How the cutting conditions, tool materials, and work materials affect tool wear and tool life.	Module B	Goal 4
Project #6: How the cutting conditions and tool geometry affect the surface roughness and the residual stress of machined parts.	Module C	Goal 5

Table 2. Data generated by using the computer simulation program

Tool–chip friction parameter	The predicted shear-plane angle (degrees)
0.10	44.0
0.25	40.8
0.40	36.2
0.55	31.3
0.70	25.8
0.85	18.9
0.93	13.8

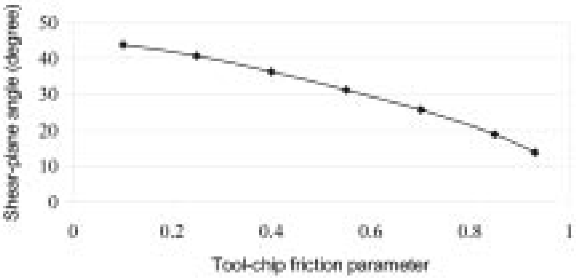

Fig. 3. The tool–chip friction vs. the shear-plane angle.

tool–chip friction and generated a set of data as shown in Table 2.

The student then saved the data in an Excel file and plotted the relationship between the tool–chip friction and the shear-plane angle as shown in Fig. 3.

Based on the results in Fig. 3, the student drew the following conclusion: "The shear-plane angle decreases as the friction parameter increases. This data is nonlinear. I think the shear-plane angle drops because the tool pushes the material more and the material sticks to the front edge of the tool causing more build-up which decreases the shear-plane angle." The student's observation is generally correct in many machining situations. He also made an effort to analyze and explain the conclusions he made.

EVALUATION OF STUDENT LEARNING OUTCOMES

Students' attitudes and experiences toward our computer simulation program

To survey students' attitudes and experiences regarding our computer simulation program, we designed a questionnaire with both Likert-type and open-ended questions. Table 3 shows the questionnaire that we administrated at the end of the semester.

A total of 20 students responded to the questionnaire. Figures 4 and 5 show the breakdown of student responses to the first two Likert-type questions.

From the results shown in Figs 4 and 5, 18 students (90%) rated their learning experience as positive or very positive, and 17 students (85%) rated the quality of the computer simulation program as high or very high. None of students rated their experience as negative or the quality of the computer simulation program low. The computer simulation program with its immediate feedback allows the students to accurately construct their knowledge and understanding. Constructivist learning theory [24, 25] has demonstrated, again in our case, greater levels of understanding and knowledge retention.

Table 3. Questionnaire for evaluating students' attitudes and experiences

Questions	
1	Compared with other engineering classes, please rate your experience using the computer simulation learning modules: Very negative 1 2 3 4 5 Very positive
2	I would like to rate the quality of the simulation modules as: Very low 1 2 3 4 5 Very high
3	Please explain any specific thoughts or attitudes about the course that have changed for you as a result of using these simulation modules.
4	Please describe to what extent did the computer simulation help with your conceptual understanding of the course content.
5	What part of the simulation modules did you like the most?
6	What part of the simulation modules did you dislike the most?
7	What part of the simulation modules did you learn the most from?
8	What part of the simulation modules could be improved? • The overall way the simulation modules looks/ the display • How easy it is to use the simulation modules • The colors and the print used in the display • The simulation modules itself • The length of the simulation modules • The information in the simulation modules • Other items not mentioned above

In the students' written comments on how the computer program helped improve their learning, it is found that the words/phrases most frequently used by the students included:

- see
- visualization
- easy to use
- real-time.

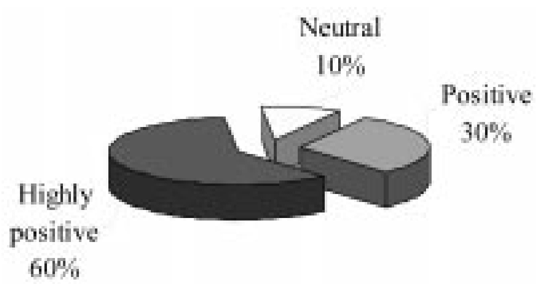

Fig. 4. Students' rating of their experience with the computer simulation program.

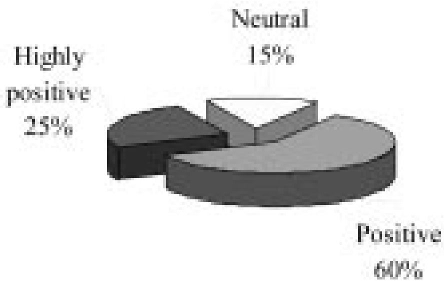

Fig. 5. Students' rating of the quality of the computer simulation program.

The following are some selected examples of students' comments.

- I am a visual person—seeing the effects of making parameter changes (as I make the changes) help me to understand what is happening better than just looking at a schematic of the tool and workpiece on paper.
- When I can see what I have learned, it increases my ability to learn.
- It helped me to learn trends and dependencies. I was able to visualize how the chip formation changed and which parameters were significant. I am a visual learner.
- I can easily see what is happening or changing with the changes in parameters. It is nice to get out of straight lectures and have some hands on projects.
- I really like being able to see how the different cutting conditions affect the forces and the chip thickness without having to do a lot of hand calculations.
- It gave me a better idea about the effect of changing a particular parameter.
- The simulation helps me a lot because it is much fun playing with the dials in the program and then reading about it in the textbook.
- It is very helpful to be able to instantly see the relationship between cutting conditions, tool geometry, cutting forces, and work materials. I think repetition is an important step in learning concepts and this class has found a good way -using the simulations- to incorporate repetition without demanding 10 hours a week of homework. I enjoy the simplicity of the modules and easily adjustable parameters.

Enhancing students' fundamental understanding of machining with computer simulations

The assessment of student learning outcomes and the assessment of the effectiveness of computer simulation program are integrally related. The following two assessment questions were of particular interest.

1. Could computer simulations enhance (or reinforce) the students' learning of the objectives covered in the classroom lectures? This question addresses the effectiveness of computer simulation program.
2. Could computer simulations help students gain a higher level of understanding concerning the complex relationships between various machining parameters? It was important to determine if and when computer simulations could be used for students to apply their knowledge to new situations indicating a movement on the continuum from novice to expert.

A unique instrument was developed to investigate these two questions. The instrument included the use of a set of multiple-choice questions at varying degrees of difficulty. Table 4 shows one example in which students were required to answer four technical questions with or without the assistance of a computer simulation program. The four questions were on a continuum from the easiest to the most difficult. The first three questions represented specific technical contents covered in the classroom lectures in which the relationships among relevant machining variables were not explicitly explained to the students. Question four was not directly addressed in the classroom lectures and required students to make connections among various topics that they have learned in order to correctly answer it.

The following instruction was provided to the students.

- First, select a response without the use of the computer simulation program.
- Next, check one of the three middle columns indicating your level of confidence with your first response. If you are 'very sure' of your first response, there is no need to run the computer simulation program. Just write your first response in the final response column. If 'somewhat' or 'not sure' of your first response, run the computer simulation program to learn, and then write your answer in the final response column.

A total of 20 students answered the four questions and indicated their confidence level for each question. This generated a total of 80 student answers to the confidence level for the four questions. The results for each question are shown in Fig. 6. All 20 students answered all four questions correctly in their final response. The first, and also the easiest, question was answered with a 'very sure' level of confidence by 80% of the students. Only 20% felt it was necessary to confirm their answer by running the computer simulation program. However, as the difficulty level of the questions increased from question two to four and required the students to apply their knowledge to new situations, the students' confidence levels decreased, and their reliance on computer simulation program increased as expected.

In summary, a total of 57 student answers (71 percent of the 80 student answers) stated that computer simulations were necessary ('not sure') or preferred ('somewhat sure') to confirm their first response to the four technical questions. This

Table 4. Multiple-choice technical questions for assessing student learning

Technical questions	First response answer	Confidence level			Final response answer
		Very sure	Somewhat sure	Not sure	
1. Increasing the feed rate: a) reduces the cutting force b) reduces the thrust force c) reduces the average temperature at the shear plane d) increases the chip thickness					
2. Increasing the cutting speed: a) reduces the cutting force b) increases the thrust force c) increases the resultant force d) reduces the average temperature at the shear plane					
3. Increasing the tool rake angle: a) increases the cutting force b) increases the shear-plane angle c) increase the average temperature at the shear plane d) increases the chip thickness					
4. Increasing the tool-chip friction: a) reduces the cutting force b) reduce the chip thickness c) reduces the average temperature at the shear plane d) reduces the shear-plane angle					

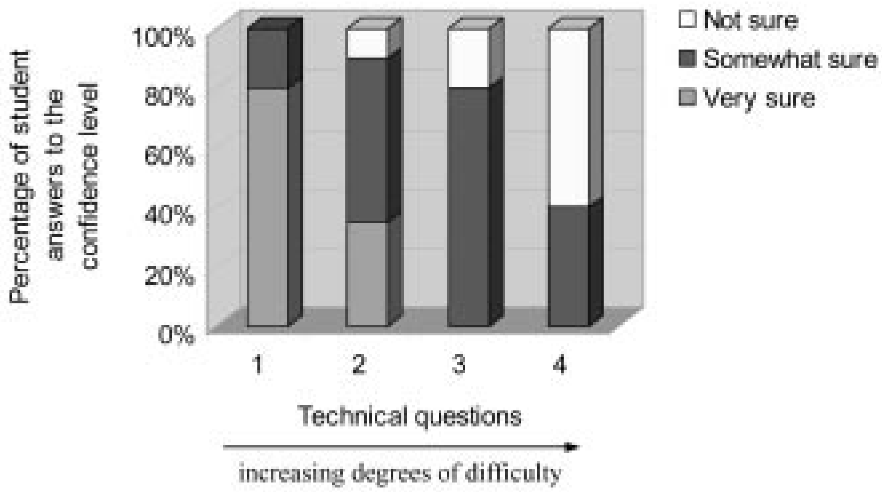

Fig. 6. Student answers to the confidence level of each technical question.

evidence shows that computer simulations did enhance student learning and did help students gain a higher level of understanding concerning the complex relationships between various machining parameters, especially when learning contents are not explicitly covered in the traditional classroom lectures. Therefore, our answers to the previously-stated two assessment questions are both 'yes.'

CONCLUDING REMARKS

Computer simulations have become, and will continue to be employed as, one of the most powerful tools to assist in teaching and learning in modern engineering education. In this paper, we have described our recent efforts in developing and implementing a computer simulation program to assist student learning of metal machining, which is one of the most common manufacturing courses to which many students are exposed. Our research findings show that computer simulations, if properly designed and implemented, do help many students learn better. This is because many students are visual learners [19] and computer simulations provide a visual learning tool for students to instantly see results.

In conclusion, we also would like to share a final experience with the engineering and technology education community. That is, we found that computer simulations can achieve their best efficacy if properly used in combination with other types of teaching and learning activities. In our teaching, we adopted not only computer simulations but also many other instructional strategies, such as a guest speaker series involving industrial professionals, as well as real-world manufacturing laboratory experiments. In these activities, we often referred 'back' to the computer simulation projects that the students had done or would do, so the students could make connections and build a bridge between theory and practice. We learned that diversified instructional strategies not only increase students' motivation and effectiveness of learning fundamental concepts and theories but, more importantly, improve their skills to apply what they have learned to analyze and solve practical engineering problems.

Acknowledgements—This material is partially based upon work supported by the National Science Foundation under Grant No. 0536415. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

REFERENCES

1. National Research Council, *Evaluating and Improving Undergraduate Teaching in Science, Technology, Engineering, and Mathematics,* The National Academies Press, Washington, D.C., (2003).
2. F. C. Fang and D. Pines, Enhancing transportation engineering education with computer simulation, *Int. J. Eng. Educ.*, **23**, 2007, pp. 808–815.
3. W. L. Chan and Z. Qu, Using XML/Java to enhance an online learning architecture for engineering education, *Int. J. Eng. Educ.,* **21**, 2005, pp. 288–296.
4. J. Liu and R. G. Landers, Integrated modular machine tool simulation for education in manufacturing automation, *Int. J. Eng. Educ.,* **20**, 2004, pp. 594–611.
5. J. P. Keller, Teaching PID and fuzzy controllers with LabVIEW, *Int. J. Eng. Educ.,* 16, 2000, pp. 202–211.
6. N. M. Avouris, N. Tselios and E. C. Tatakis, Development and evaluation of a computer-based laboratory teaching tool, *Computer Applications in Engineering Education,* **9**, 2001, pp. 8–19.
7. A. A. Renshaw, J. H. Reibel, C. A. Zukowski, K. Penn, R. O. McClintock and M. B. Friedman, An assessment of on-line engineering design problem presentation strategies, *IEEE Transactions on Education,* **43**, 2000, pp. 83–89.
8. L. Whitman, D. Malzahn, V. Madhavan, G. Weheba and K. Krishnan, Virtual reality case study throughout the curriculum to address competency gaps, *Int. J. Eng. Educ.,* **20**, 2004, pp. 690–702.
9. W. A. Ross and S. Aukstakalnis, Virtual reality: potential for research in engineering education, *Journal of Engineering Education,* **83**, 1994, 287–291.
10. V. M. Eller, S. E. Watkins, R. H. Hall, J. Balestra and A. S. Rao, Multimedia web-based resources for engineering education: the media design and assessment laboratory at UMR, *Proceedings of the 2001 American Society for Engineering Education Annual Conference & Exposition,* June 24–27, Albuquerque, New Mexico, (2001).
11. A. Azemi, Using multimedia courseware in engineering education, *Proceedings of the 1996 Frontiers in Education Conference*, November 6–9, Salt Lake City, Utah, (1996).
12. P. C. Chang, R. H. McCuen and J. K. Sircar, Multimedia-based instruction in engineering education: Strategy, *Journal of Professional Issues in Engineering Education and Practice,* **121**, 1995, pp. 216–219.
13. J. Bourne, D. Harris and F. Mayadas, Online engineering education: Learning anywhere, anytime, *Journal of Engineering Education,* **94**, 2005, pp. 131–146.
14. J. Flowers, Online learning needs in technology education, *Journal of Technology Education,* **13**, 2001, pp. 17–30.
15. W. Clark and D. DiBiasio, Computer simulation of laboratory experiments for enhanced learning, *Proceedings of the 2007 American Society for Engineering Education Annual Conference & Exposition,* June 24–27, Honolulu, Hawaii, (2007).
16. K. Rosentrater and J. Visser, Simulation as a means to infuse manufacturing education with statistics and DOE—a case study using injection molding, *Proceedings of the 2007 American Society for Engineering Education Annual Conference & Exposition,* June 24–27, Honolulu, Hawaii, (2007).
17. V. Sheyman, Computer simulation of thermodynamics experiments, *Proceedings of the 2007 American Society for Engineering Education Annual Conference & Exposition,* June 24–27, Honolulu, Hawaii, (2007).
18. R. M. Felder and L. K. Silverman, Learning and teaching styles in engineering education, *Journal of Engineering Education,* **78**, 1988, pp. 674–681.
19. J. D. Bransford, A. L. Brown and R. R. Cocking, *How People Learn*, The National Academies Press, Washington, D.C., (2000).
20. J. W. Pellegrino, N. Chudowsky and R. Glaser, *Knowing What Students Know—The Science and Design of Educational Assessment,* The National Academies Press, Washington, D.C., (2001).
21. N. Fang and W. Wang, Influences of the material shear flow stress and the shear-plane angle on the size effect in machining, *Transactions of the NAMRI/SME,* **33**, 2005, pp. 421–428.
22. N. Fang and G. Fang, Theoretical and experimental investigations of finish machining with a rounded edge tool, *Journal of Materials Processing Technology*, **191**, 2007, pp. 331–334.
23. N. Fang and Q. Wu, The effects of chamfered and honed tool edge geometry in machining of three aluminum alloys, *International Journal of Machine Tools and Manufacture*, **45**, 2005, pp. 1178–1187.

24. J. Bruner, *The Process of Education*, Harvard University Press, Cambridge, Massachusetts, (1960).
25. J. G. Brooks and M. G. Brooks, M. G. *In Search of Understanding: The Case for Constructivist Classrooms,* Association for Supervision and Curriculum Development, Alexandria, Virginia, (1993).

Ning Fang is an Associate Professor in the Department of Engineering and Technology Education at Utah State University. His areas of interest include curricular reform in engineering education, computer-assisted instructional technology, the modeling and optimization of manufacturing processes, and lean product design. He earned his Ph.D., MS, and BS degrees all in Mechanical Engineering and is the author of more than 60 technical papers published in refereed international journals and conference proceedings. He is a member of the American Society for Engineering Education, a member of the American Society of Mechanical Engineers, and a Senior Member of the Society for Manufacturing Engineering.

Gary A. Stewardson is an Associate Professor in the Department of Engineering and Technology Education at Utah State University. His Ph.D. is in technology education. His areas of interests include manufacturing, automation and control systems; curriculum development; and instructional strategies. His current research and creative endeavors focus on the development of innovative curriculum in the areas of engineering and technology education utilizing problem solving and design instructional strategies. He is a member of the American Society for Engineering Education and International Technology Education Association.

Margaret M. Lubke is an Assistant Professor in the Research and Evaluation Methodology Unit in the College of Education and Human Services. Her research areas of focus include evaluation of educational research as well as the design and development of web-based data systems. She is a member of the American Evaluation Association.