EXPERIENTIAL LEARNING
IN MANUFACTURING
SYSTEM DESIGN$^1$

by

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ABSTRACT
Industry has been calling for more breadth in engineering education for many years. In particular, the challenges of competition in manufacturing engineering call for greater management skills in new graduates. We describe a course in manufacturing system design that attempts to address this need using integrative design experiences.

INTRODUCTION

The message from industry to engineering schools for the past decade has been clear: engineers entering the workforce must have a broader set of skills and competencies to supplement their expertise in engineering analysis. In particular, the manufacturing engineer of the future increasingly will be called upon to act as a systems integrator, integrating functional areas as diverse as marketing, design engineering, facilities planning, manufacturing process engineering, human resources, information systems, and managerial accounting [Koska and Romano, 1988]. This new role requires a breadth of knowledge and a level of management and leadership skills considerably beyond that traditionally expected of engineering graduates. Spurred by pressures and incentives from many sources, universities are responding to these demands by introducing new programs and degree options, by innovating within existing curricula, and by changing fundamentally the techniques of educational delivery. The rate of progress has been slow but the purpose of this paper is to document the results of one sustained effort to redefine engineering education along these lines.

The focus of this paper is on a single course: Design of Manufacturing Systems, taught at Cornell University at the senior level (ORIE416) to students of Operations
Research and Engineering and at the masters level (ORIE 515) to students from all engineering disciplines enrolled in the Manufacturing Option of the Master of Engineering Program. While this course is only a small portion of the overall engineering curriculum, the changes that are taking place here have broad implications for engineering and management education in general.

This course has its roots in the continuing education programs of IBM's Manufacturing Technology Institute (MTI). In the early 1980's, under IBM sponsorship, we began developing educational modules that would be appropriate both for students in our undergraduate and master's engineering curricula as well as for the experienced engineers and managers in MTI's programs. We discovered for ourselves that the techniques of hands-on design and simulation that have been so effective in engaging continuing education students in industrial classes were equally effective in energizing our own students. For the past dozen years, we have continued these development efforts with industrial and governmental support. The course, Design of Manufacturing Systems, is the primary vehicle for delivering these materials to our students. The modules are also in use at many other universities and in many industrial training programs.

In this paper we will review the educational goals of this course, the technique of experiential learning used to achieve these goals, the integrative design experiences that constitute the course, the lessons we have learned, the techniques used to disseminate this material, and the implications for engineering education.

**EDUCATIONAL GOALS**

We have three goals in teaching a course on the Design of Manufacturing Systems:

1. to involve students in the issues of manufacturing system design;
2. to guide students through the exercise of engineering methodologies to address those issues; and
3. to lead students to increased professional maturity.
In the case of (1), we emphasize the area of material logistics but we do so within a broad context of manufacturing issues. The methodologies of (2) employed by the students are the techniques of operations research that we have found useful in our own industrial practice: simulation, inventory modelling, optimization, statistics, queueing analysis, scheduling, and economic analysis. There are opportunities in many of the educational modules to extend the analysis into the disciplines of mechanical, electrical, chemical, and environmental engineering but this has not been our focus.

By professional maturity in (3), we mean the range of team, leadership, and communication skills that industry has been asking to see improved in engineering graduates.

**Educational Technique: Experiential Learning**

To achieve the goals of this course, we have adopted the technique of experiential learning. In this course, students find themselves faced with real-world situations: routing and scheduling a fleet of trucks, operating a semiconductor packaging line, assembling hoses and fittings just-in-time to meet customer demand, or managing the production and distribution of goods in a world-wide network of suppliers, factories, and warehouses. They are making decisions in a dynamic simulation, interacting with each other, pursuing goals sometimes cooperatively and sometimes competitively. It is up to the students to figure out an operating strategy for this system and then to propose a new system design.

**The Manufacturing Operations Game**

The first such educational module that we implemented in our curriculum was the Manufacturing Operations Game [Jenner and Anderson, 1980]. In this game, a group of twelve to fifteen students sits around a conference table making decisions that control the operation of a simulated semiconductor packaging line for one production month. A microcomputer is used to record the decisions and to project status reports onto a large
screen for the entire group to view. The packaging line is a multi-stage dynamic system with unpredictable yields and non-linear responses to changes in control variables. Periodically, special situations arise such as a shortage in substrate deliveries, a yield bust in the chemical etch process, and so on. Different sub-groups of students are responsible for different control variables and a management team is responsible for bringing the group to consensus when tradeoffs are involved.

The number of students is critical for effective gameplay. If there are fewer than eight students, certain group phenomena such communication failure often do not occur. With ten or more students, the process of exploring options and bringing the group to consensus is fraught with difficulty. Thus, in addition to being an opportunity for engineering analysis, the game is an excellent opportunity to illustrate principles of group dynamics and to help students develop the skills to overcome these difficulties. The game can be played in as few as 5 hours, typically split into two playing sessions with time for analysis and discussion in between.

**Experiential Learning in Manufacturing System Design**

This game, and its companion, The Manufacturing System Development Game [Jackson *et al*, 1989] serve as models for our use of experiential learning. Each experience in ORIE 416/515 begins with a hands-on simulation game in which teams of students compete with each other in managing a dynamic system. In a debriefing session after the game, students articulate the rules and strategies they used to optimize system performance. At this point, the students are provided with extensive data that describe the real world situation upon which the game is based. Now they must re-design the system: a new manufacturing system for the next generation product, a new way to move product to the customer, a new way to schedule equipment, or a new strategy for satisfying global demand. Working in teams and employing tools and techniques from operations research, the students must present a comprehensive design solution complete with a formal
Capital Acquisition Request. They present their results to a panel of faculty and industry representatives in both oral and written form. Their success here determines their grade. The faculty serve as facilitators along the way: encouraging the students' efforts, challenging their analysis, and suggesting further issues to consider.

**Powerful Attributes of Experiential Learning**

From the beginning, student response to this style of education has been enthusiastic. A sampling of some of the student evaluations [Jackson, 1994] reveals that this course really has something new to offer. "Thank you for a great course. I really learned a lot." "The great thing with this class is that it is a Socratic class where we learn by ourselves, led toward the important points." "I love doing this stuff!" "...this was an excellent course to wrap up my ... curriculum with." "I liked the learning by doing - the hands-on aspect of the course." "I worked hard, learned a lot, and had fun. These three things very seldom came together in my academic life." "... one of the best educational experiences I have ever had. I would like to ... congratulate both Professors Jackson and Muckstadt..."

The high level of student motivation in the course clearly comes from the fact that throughout the simulation and design experience, the students "own the problem." As a result, the issues that arise are their issues and not simply academic topics. Students who would have fallen asleep during a lecture on concurrent engineering have a different perspective when their portion of a design is held up because they must wait for another team to give them data. In this way, the experiences provide a context for the faculty to discuss topics with the students and to introduce techniques as they are needed.

These experiences demand teamwork and by their nature force the integration of topical and technical areas. Students completing such a course of study say they are better problem solvers.
Experiential learning is not a panacea for all the difficulties in engineering education. In particular, it is not an efficient method for transmitting a large body of technical material. For example, the level at which any of the operations research techniques are discussed in this course would be considered to be superficial in any course dedicated to the technique. On the other hand, experiential learning is highly effective for motivating students, for providing context, for providing opportunities to apply technical skills, and for building team, leadership, communication, and problem solving skills. It answers a clear need in engineering education.

**INTEGRATIVE DESIGN EXPERIENCES**

Over the past dozen years, together with our graduate students and collaborators from industry and from other universities, we have assembled four major integrative design experiences, each following the general model described above:

1. The Manufacturing System Development Game [Jackson, Jenner, and Muckstadt, 1989];
2. Llenroc Plastics: Market-Driven Integration of Manufacturing and Distribution Systems [Jackson and Muckstadt, 1990];
3. The Velocity Manufacturing Company [Muckstadt and Severance, 1992]; and

Each of these design experiences are comprised of games, analytical software tools, situation databases, and casebooks. Several now are supplemented with multi-media resource files and instructor's manuals. These design experiences are briefly described in [Jackson et al, 1993] and in greater detail in the referenced papers.

**LESSONS LEARNED**

We have not perfected the techniques of experiential learning. However, we do see some principles worth sharing. First, it is important to understand the limited role of the computer. We have developed a variety of computer-based educational modules over the years. The tutorial-style educational modules that attempt computer aided instruction
have not had anything like the success of those modules which use the computer to enable experiential learning. Simply put, the computer is not the teacher.

Second, the instructor has a critical role to play. Although students relish the games and simulations, they frequently solve them using intuition or trial and error. When challenged, they are unable to justify their actions. In many cases, they cannot even put their strategy into words. We use debriefing sessions to force students to articulate their strategies and to identify underlying principles. During the design phase of the experience, it is important for the instructor to continually encourage the students to employ the scientific method to resolve design issues.

Third, when developing these materials it is important to keep the structure simple. It is very easy to keep adding features that increase the realism of the experience. Unfortunately, it is possible to overwhelm students with detail and complexity. Students must be able to grasp the issues and solve the problems in a relatively short amount of time. For example, when using the Manufacturing System Development Game, we found that, for the first week of the experience, students were very anxious until they had a grip on the full range of issues that we were trying to cover. To reduce that anxiety, we had to create a number of additional modules to help guide the students through this process. In the later integrative design experiences, we have been more careful to structure the experience for the student.

As a final lesson, we encourage other faculty who venture into this area to work collaboratively. Both the development and the teaching efforts benefit enormously when individuals with different perspectives, expertise, and teaching styles interact. We have been fortunate to work with many others in this enterprise and we are happy to share the credit for the success of this effort with them. John Jenner of ChangeLab International, and Dennis Severance and David Murray of the University of Michigan have been co-developers of these design experiences. Of the dozen or more graduate student
developers, we make particular mention of Sarah Stock, Colin Bryar, John Muckstadt, Jr., Alex Holt, Jim Smith, Barbara Spang, Wendy Jones, and Susan Forsythe.

**DISSEMINATION TECHNIQUES**

It is our hope to see the materials we have developed used as widely as possible. Already, more than twenty universities are using some portion of them. At present, we are using two techniques to disseminate the materials: the Internet and Summer Workshops.

**Internet**

Many of the educational modules are available free of charge over the Internet. They are currently located at [tomcat.synthesis.cornell.edu/pub/Jackson](http://tomcat.synthesis.cornell.edu/pub/Jackson). They are available as zip files through anonymous ftp. WWW users can get a hypertext overview of the educational materials using the following URL:

`file://tomcat.synthesis.cornell.edu/pub/Jackson/overview.html`.

**Summer Workshops**

Workshops have proven to be the most effective means of transferring these course materials to other universities. On a compressed timetable, workshop attendees are given the task of solving the same problems faced by the students. Solutions and teaching strategies are reviewed in discussion sessions. In this way, prospective instructors acquire a student's view of the learning experience and, at the same time, master the software and teaching objectives associated with the modules.

It is our experience that use of these modules practically requires team teaching. Consequently, we recommend that two instructors from the same institution, or at least one instructor and a teaching assistant, attend the workshop.

The next workshop will be offered at Cornell University during Summer 1994. Current details of this and future workshops may be obtained from the Center for
Manufacturing Enterprise, Cornell University, 106 Engineering and Theory Center, Ithaca, NY 14853-3801 (Tel. (607) 255-7757) or from the WWW address listed above.

IMPLICATIONS FOR ENGINEERING EDUCATION

As we have noted, the course Design of Manufacturing Systems is only a small part of our engineering curriculum and the technique of experiential learning is not a panacea for all the problems of engineering education. On the other hand, we believe that it represents a new and emerging educational paradigm, one that places the emphasis on the student before the instructor, on the problem before the abstraction, and on the context before the specifics. It requires students to work in teams. It also requires faculty to work in teams. It involves synthesis as well as analysis. It is a direct response to industry asking for more breadth of ability in graduating engineers.

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Professor Muckstadt is Director of the School of Operations Research and Industrial Engineering. He studied at the University of Rochester for the A.B. degree in mathematics and at the University of Michigan for the M.S. in Industrial Administration, the M.A. in Mathematics, and the Ph.D., granted in 1966, in Industrial Engineering. He joined the Cornell faculty in 1974 after twelve years of active military service as a faculty member of the Air Force Institute of Technology and an operations research analyst at the Air Force Logistics Command Headquarters.

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