THE LEARNING FACTORY - INTEGRATING DESIGN, MANUFACTURING AND BUSINESS REALITIES INTO ENGINEERING CURRICULA - A SIXTH YEAR REPORT CARD

John S. Lamancusa[1], Jens E. Jorgensen[2], José L. Zayas-Castro[3], Lueny Morell de Ramirez[4]

Abstract — The Learning Factory is an industry-university partnership to produce world-class engineers by integrating design, manufacturing and business realities into the engineering curriculum. It integrates a practice-based curriculum and physical facilities for product realization. It began in January 1995 with ARPA/NSF funding as a partnership of Penn State University, University of Puerto Rico-Mayaguez, the University of Washington and Sandia National Labs. After 6 years, and now self-supporting, the accomplishments of this multi-university partnership include:
Facilities: the Learning Factory - 17,000 ft^2 of modern, hands-on facilities for design and manufacturing at 3 universities, used by more than 2500 students per year;
Curriculum: 4 new courses and degree programs in product realization;
Industry Interaction: over 200 industry partners, industry advisory boards for curriculum and facility feedback, over 200 interdisciplinary industry-sponsored projects per year;
Outreach: 33 publications, 17 national and international workshops, and curriculum materials available on the web at www.lf.psu.edu

Index Terms – Learning Factory, industry capstone projects, integrating design and manufacturing, product realization

INTRODUCTION

The Learning Factory (LF) is the outcome of The Manufacturing Engineering Education Partnership (MEEP), which was formed in January of 1995 as the result of a grant from the ARPA Technology Reinvestment Program in Manufacturing Engineering Education. MEEP consists of Penn State, The University of Puerto Rico- Mayagüez, the University of Washington, Sandia National Labs, and industrial affiliates. A total of 43 faculty participated either in program management, course design, Learning Factory development, or industrial advisory board coordination. A description of the overall program can be found in reference [1]. The specific objectives of our partnership are to implement:

- A practice-based engineering curriculum which balances analytical and theoretical knowledge with manufacturing, design, business realities, and professional skills;
- Learning Factories at each partner institution, integrally coupled to the curriculum, for hands-on experience in design, manufacturing, and product realization;
- Strong collaboration with industry through advisory boards and industry-sponsored capstone design projects;
- Dissemination to other academic institutions, government and industry.

The Learning Factory's mission is to integrate design, manufacturing and business realities into the engineering curriculum. This is accomplished by providing balance between engineering science and engineering practice. The Learning Factory is the result of listening to the stakeholders in the education process – industry, faculty and students. Our industrial partners tell us that they want to hire engineers who can communicate, work in teams and who can design and build real hardware, not just computer simulations. In order to do so, they must possess strong technical competence in engineering science fundamentals, as well as design and synthesis skills that enable them to effectively apply those fundamentals to solve real problems. Students desperately need to exercise their creativity and want to see applications as well as theory. Faculty aspire to be effective educators but need resources and facilities to reap the full benefits of active learning.

COMBINING THEORY AND PRACTICE

Learning Factory Facilities

Physical facilities for manufacturing and product realization, located at each partner institution, are the cornerstone of our efforts. Across our coalition, over 17,000 square feet of new and remodeled facilities, equipped with state-of-the-art equipment, are devoted to this activity. Each university has its own Learning Factory with basic capabilities including

[1] John Lamancusa, Penn State, Mechanical Engineering Dept., Univ. Park, PA 16802, jsl3@psu.edu
[2] Jens Jorgensen, University of Washington, Jorgen@uwashington.edu
[3] Jose Zayas-Castro, University of Missouri – Columbia, zayascastroj@missouri.edu
[4] Lueny Morell de Ramirez - University of Puerto Rico- Mayagüez, lueny@centennialpr.net

machine tools, workbenches, hand tools, welding, metrology, reference materials, student meeting areas, and CAD/CAM workstations. In addition, specialized facilities, such as CNC machining, injection molding, coordinate measurement machines, electronic assembly, PVC processing, metal foundry and rapid prototyping are located at one or more of the universities and are available to the other partners.

In the Learning Factory, students actively experience the product realization process in its entirety, from customer need, design concept and finished hardware. Our vision is a facility where students can:

- Learn by experience
- Apply their theoretical knowledge to solve real problems
- Develop common sense and judgment,
- Learn to work with persons of all motivational and educational levels
- Develop an appreciation for the skills of other disciplines
- Learn from their errors – *Good judgment comes from experience – experience comes from bad judgment*
- Discover that not every part designed in 256 colors on a Pentium workstation can be economically fabricated, nor will it function perfectly the first time
- Discover that everything takes longer than planned

The Learning Factory is an on-demand facility that is designed to be used across the curriculum, and across multiple departments, analogous to the way one might use a library. It differs from traditional, highly focused labs that are owned by a particular department. These labs are typically tied to specific courses such as fluid mechanics, electronics, or automatic controls, and may be used only sparsely during a typical academic week. Often, a course cannot justify having a lab of its own, and so an educational opportunity is lost. In contrast, the Learning Factory is a shared, open access facility, used by many departments and courses. One of the most educational aspects of the Learning Factory is its melting pot nature, where students from many majors rub elbows and learn from each other. The Learning Factory is continuously supervised by trained personnel and can be scheduled by any engineering class requiring design, manufacturing and assembly facilities. Training classes are offered to instruct students in safety, basic machining, welding and CAD software. The Learning Factory is open days, evenings, and weekends for general student use, provided students have the appropriate training certification.

In addition to its direct educational value, the physical presence of the Learning Factory serves important psychological purposes. Bricks and mortar imply a permanence and importance not achieved by a written course description in a university catalog. Enterprising students naturally gravitate to these facilities and they provide a kind of home and social identity. A modern manufacturing facility, filled with creative students and on-going projects, is perhaps the most effective argument for convincing industry partners, recalcitrant faculty, and university administrators of the value of the practical side of engineering education.

Practice Based Curriculum

An interdisciplinary curriculum in Product Realization is available as a minor or a degree option at the participating universities. Several departments at each school are cooperating in offering this curriculum, including: Mechanical, Industrial, Chemical, Electrical Engineering and Business. The curricula, consist of a progression of manufacturing/design courses, approximately one per term, and allow students to practice engineering science fundamentals in the solution of real problems. As part of the new curricula, four new courses in Product Dissection, Concurrent Engineering, Technology Based Entrepreneurship, and Process Quality Engineering have been developed. In addition, a number of existing courses have been modified to take advantage of the Learning Factory concept. Details of these courses, as well as course materials may be found at ***www.LF.psu.edu*** . The courses developed by MEEP are:

1) Product Dissection*:* This course examines the way in which products and machines work: their physical operation, the manner in which they are constructed, and the design and societal considerations that determine the difference between success and failure in the marketplace. The primary objectives of this course are to develop a basic aptitude for engineering and engineering design, and to develop mental visualization skills by examination of the design and manufacture of consumer and industrial products. Dissection exercises include bicycles, single use cameras, household appliances, telephones and IC engines.

2) Concurrent Engineering: This course discusses the role of concurrent engineering in modern engineering companies. Students gain an appreciation for formal product/process development strategy, and learn how to use tools such as team decision making processes, value engineering, quality function deployment, project networks and planning, failure mode and effects analysis and DFM/DFA assessment tools. Also discussed are life cycle issues such as safety, reliability, maintainability and product disposal. Case studies from various industries provide students with a broad vision of concurrent engineering, and industry speakers present a practical perspective.

3) Technology Based Entrepreneurship: This course is taught in conjunction with the School of Business. It is designed for engineering, science, and business students interested in learning about entrepreneurship from a technology and practice-based point of view. The emphasis of the course is on innovation and creativity. Topics include: market analysis, problem and idea selection, prototyping, and product design.

4) Process Quality Engineering: This course exposes students to the importance of statistical and probabilistic methods. Students learn to apply probability models and statistical tools to engineering problems. The course includes eight laboratory sessions, where students design their own experiments, collect data, and apply appropriate statistical analysis tools to that data.

IMPACT AND ACCOMPLISHMENTS

The overall impact of this project has been to instigate change in the academic culture. The key lever in achieving this has been the positive influence of our industrial partners. Their participation is convincing our administrations and faculties that a practice-based, hands-on learning environment, in complement with engineering science, is a valid educational approach. Specific accomplishments of this program at the three universities are described below. These accomplishments illustrate the richness and diversity of this approach and attest to the cross-fertilization which resulted from this partnership. During the last three years, MEEP has given seventeen workshops in the USA, Latin America, Czech Republic and Turkey to share these results and assist others along this path.

Penn State Accomplishments

Facilities Description

- Original Facilities (built in 1995) administered by the College of Engineering: Machine Shop (2500 ft^2) – a full function manufacturing shop including manual and CNC machining, rapid prototyping, welding, assembly and test areas; Design Studio/Computer Lab (1000 ft^2) – 10 Pentium CAD/CAM workstations, resource library, student conference and meeting area
- New Facilities as of Summer 2001: Model Shop (1500 ft^2) – light machine shop for plastic and wood prototyping; Dissection/Design Studio (1500 ft^2) – work benches and hand tools for model making, product dissection, electronic prototyping, team activities

Facilities Usage

- 12 courses, from freshman through graduate programs, involving over 700 students from all engineering majors, used the Learning Factory in 2000
- 1000 students attended training courses (non-credit, free, voluntary) in safety, basic machining, welding
- Student Competition Projects: Formula SAE, Future Truck, ASCE Steel Bridge, NASA Spirit Rocket (100 students)
- K-12 programs, programs to enhance gender and cultural diversity in engineering (80 students)

Curriculum

- The four MEEP-developed courses are continuously taught by 3 departments: (ME-Product Dissection, IE-Concurrent Engineering, EE-Entrepreneurship, IE-Process Quality Engineering). 270 students enrolled in MEEP courses in the 2000/2001 academic year.
- 10-15 students complete the ***Product Realization Minor*** each year

Industry Interaction and Projects

- 266 industry-sponsored interdisciplinary senior design projects have been completed for 79 companies since January of 1995. 56 projects, employing 280 students in Mechanical, Industrial, Electrical and Computer Science and Engineering, were completed in the most recent academic year. Companies contribute a fee ($1800 per student team) to cover project expenses and Learning Factory overhead.
- Recent industry sponsors cover a broad range of industries: Advanced Glassfiber Yarns, Agilent, Atotech, BAE Systems, Corning, Decorator Industries, Delphi, FCI Electronics, Honda, IBM, Ingersoll Rand, JLG, Kennametal, Kimberly Clark, Kodak, Lear, Mascotech, Microsoft, New Holland, New Pig, Pratt and Whitney, Texaco, Visteon and Westinghouse.
- An Industry Advisory Board meets four times each year to oversee the program, provide customer feedback and plan for future activities

Awards

- Honorable mention for curriculum innovation, ASME - 1996
- PSU Provost's Award for Collaborative Instruction and Curricular Innovation 1996
- Boeing Outstanding Educator Award 1998
- Exemplary Program Award – Corporate and Foundation Alliance 2000
- Numerous industry and private benefactor contributions
- Numerous faculty engaged in this project have earned outstanding teaching awards from the university

Impact

- Since 1996, Penn State's Learning Factory has nearly doubled in size and tripled in usage. While demand continues to increase, usage is presently constrained by the size of the facility.
- The Learning Factory has enabled the complete overhaul of our capstone design courses in Mechanical, Industrial and Electrical Engineering to utilize industry projects and inter-departmental teams, impacting approximately 300 students per year.
- We recently held our 13th ***Project Showcase***, a trade show event featuring more than 60 student design and entrepreneurial projects from freshman year through

graduate programs. This event is held at the end of each semester and is attended by over 400 people including the general public, high school students, industry sponsors, university students, and faculty.

Future Plans

The College of Engineering is planning a new building which will become the permanent home of an expanded Learning Factory in 5-7 years.

University of Washington Accomplishments

Facilities Description:

- Main Facility, administered by ME department, (6,600 ft^2): Product Dissection Lab (1,400 ft^2), Design Computer Lab (1400 ft^2), Design Studio (800 ft^2), Mechatronics Lab (1,000 ft^2) and Project Work Area (2,000 ft^2). In addition, we have an adjacent student Machine Shop (2,400 ft^2)
- Design Library - to provide students with services, reference material (catalogs, vendor literature, past project reports etc.) not found in the university library systems.

Facilities Usage

- The SAE Formula Car project typically involves 40 students from Mechanical and Electrical Engineering and the School of Business.
- The Human Powered submarine attracts 15 -20 students per year, mostly from mechanical engineering
- The Fuel Cell Technology program has 30 mechanical engineering and 10 chemical engineering students
- The Mechatronics Option has 20 - 25 students involved in 5 - 6 projects per year. Half the projects have industrial sponsorship.

Curriculum

- The Product Dissection course is offered annually and attracts 34 students (max lab capacity). The Entrepreneurship and Concurrent Engineering Courses have not been staffed the last two years but new faculty arrivals in both ME and IE will revitalize these courses
- The ENGR 100 *Introduction to Design* course has become a very sought after course by the freshman. It is open to all students (engineering and non-engineering). The course is team based with an equal emphasis on product dissection, product design, and technical communication.
- The Capstone Design projects with industrial sponsorship are now a two-quarter sequence (20 weeks) with the expected deliverable of a working prototype.

Industry Interaction and Projects

- 20 sponsored design projects are completed each year with teams of 3 -5 students. Design teams are becoming more interdisciplinary with participation from Electrical, Chemical, and Industrial Engineering as well as students from the Business School.
- A web based system for collaborative design interactions with clients away from the Seattle Metropolitan was implemented two years ago and has proved a success with students, industry clients and faculty participants

Awards

- A University curriculum improvement grant allowed us to restructure the Learning Factory space to: expand enrollment activities in the freshman *Introduction to Design* course from 198 to 431 students in the 2000/01 academic year; upgrade facilities for student team activities; and upgrade space to allow project prototype assembly and testing
- The Boeing Company provided $175,000 for new equipment in the student machine shop. This allowed us replace 'vintage' equipment with 4 new lathes, one CNC lathe, and two CNC milling machines. In addition, we received other smaller industry grants to upgrade metrology and mechanical gauging equipment.
- A grant from Intel will replace the 15 work stations in the Learning Factory Design Lab and 12 computers in the Product Dissection Lab

Impact

The Freshman *Introduction to Design* and the *Senior Capstone design Projects* have provided the greatest educational benefit to the students. Exit surveys of graduating students strongly support the educational opportunities that the Learning Factory provides. The 'hands-on' teaching concept and project based learning has excellent industry support. They see our Learning Factory activities as a significant opportunity to interact with students. We will host our second annual Design Projects Fair on June 1. It will showcase the student design projects for the past academic year. This event drew 500 visitors last year.

Future Plans

Mechanical Engineering will celebrate its 100-year centennial in 2003. A major capital campaign is underway with our industrial sponsors to obtain funding for professorships, scholarships, improved infrastructure, and other program expansions. A $2,000,000 goal is envisioned for the Learning Factory.

University of Puerto Rico – Mayagüez Accomplishments

Facilities

- A 4000 ft^2 central facility, administered by the Department of Industrial Engineering: electronics manufacturing, injection molding, plastic assembly, and CNC machining.
- Auxiliary facilities in Chemical, Electrical, Mechanical Engineering support pharmaceutical manufacturing, robotics and automation, and computing.

Usage

- UPRM's LF is available to all interested faculty and students. More than 15 courses make use of the facilities, serving over 600 students per year.

Curriculum

- Core MEEP/LF courses continue to be offered every year. Technology Based Entrepreneurship is offered by the College of Business and is team-taught by business and engineering faculty. Product Dissection is taught by ME, Concurrent Engineering taught by IE. ChemE offers courses in pharmaceutical operations, polymers processing, and manufacturing processes. Courses emphasize practice-based hands-on experiences, stimulate innovation and combine the use of the Learning Factory facilities, theory, classroom exercises, plant tours, and industrial involvement. They also have integrated assessment of learning outcomes.
- Certificates in Manufacturing are offered by Chemical, Electrical, Industrial, and Mechanical Engineering.
- Each engineering discipline has a capstone course. The majority of capstone courses involve industry projects, with some interdisciplinary interaction

Industry Projects

- More than 150 projects are administered each year, approximately 80% are capstone projects. There are five types of industrial projects which make use of the Learning Factory: applied research projects for graduate and undergraduate students; entrepreneurial technology based endeavors; interdisciplinary projects for engineering and business students; capstone projects in engineering; and disciplinary hands-on projects in engineering. Industrial support varies from technical and access to facilities, to advising and mentoring, to cash support.
- Industrial sponsors include low-tech companies needing engineering and business support, high tech enterprises, e.g. electronics and pharmaceuticals, and service-oriented institutions in need of computer-based innovations.

Impact

- The biggest legacy is more collaboration and interaction between faculty, departments, colleges and institutions. The MEEP/LF model was shared with (and adapted by) the University of Texas-El Paso and the University of Missouri-Columbia. The University of Texas-El Paso has adopted the product dissection course for all their incoming freshmen.
- The Learning Factory is a model for entrepreneurship, and product and process development. It is a showcase for industry, academicians and visitors. A yearly fair in Entrepreneurship and Product/Process Realization is held. Three faculty members have recently started their own companies.
- The Learning Factory is a model for graduate and undergraduate curricular development, research opportunities and outcomes-based assessment, e.g. NSF-PRECISE (graduate program in CISE), NASA-PaSCoR (undergraduate courseware and research in remote sensing and GIS), NCIIA (courseware and hands-on activities integrating wireless topics in the entrepreneurship course). MEEP/LF assessment modules and tools have become guidelines for the College of Engineering's strategy to comply with ABET 2000.

Awards

- Grants from NSF, NCIIA, Raytheon, and Microsoft for dissemination and further curricular and lab development.
- Faculty engaged in this project received the Distinguished Faculty of the Year Award.

Future Plans

- New courses in pharmaceutical operations and project management.
- Two new interdisciplinary curricular options using the LF model: Material Science and Engineering for science and engineering majors, and Wireless Science and Engineering for engineering and business majors.
- Expand collaborative efforts with other institutions. A project funded by NSF will permit adaptation of courseware at the University of Missouri.

PROGRAM ASSESSMENT

A summative assessment of the MEEP program after its first two years of operation was completed in 1997. Industry partners, students and faculty were surveyed with a written questionnaire [2]. Highlights are shown below:

Student Views

- 88% say the program allowed them to practice engineering science fundamentals in the solution of real life problems.
- 82% say MEEP courses are more fun than typical engineering courses.
- 78% believe they now have a better understanding of engineering, and feel more confident in solving real life problems.
- 80% feel more confident in their ability to teach themselves.
- 17% say they learn better from lecture than from hands-on experience.

Faculty Views

- 50% understand that their participation in MEEP was beneficial to their careers; 62% were provided with positive feedback from their supervisors.

- 14% received better student evaluations compared to regular courses.
- 64% said they had a better experience with MEEP courses, compared to regular courses.
- 57% believe that their participation in MEEP was an element for teaching/education awards and recognition; but only 10% think that their participation in MEEP was an element for their promotion/tenure.

Industry Partner Views

- 95% consider that MEEP students would be more useful to their respective industries, and 79% are more likely to hire a MEEP student over a typical student.
- 100% believe real life problems were provided.
- 89% believe communication skills were emphasized.
- 93% believe teamwork skills were emphasized.

FUTURE CHALLENGES AND OPPORTUNITIES

The major challenge and opportunity facing MEEP has been to continue operations after federal funding expired. Each institution has sought permanent funding mechanisms to support operations. These funds now come from a mixture of university and industry sources. Continuing challenges include: broadening participation to include more engineering and business departments; continuous quality improvement of the courses; dissemination of materials to interested universities; convincing faculty colleagues of the scholarly content of educational activities; expanding the base of industry partners; and insuring that these efforts continue to meet the needs of all stakeholders.

CONCLUSIONS AND LESSONS LEARNED

A unique partnership of universities, industries, and the federal government continues to integrate design, manufacturing and business realities into engineering education. This partnership has developed an integrated curriculum and physical facilities for product realization with the cooperation and assistance of over 200 industrial partners. After 6 years, these efforts are now self-sustaining and continue to thrive without federal assistance. This work has generated 33 publications, earned numerous awards and has been disseminated internationally. The lessons we learned can be summarized as follows:

Practices that worked well and are recommended:

1. Industry advisory boards for strategic guidance, political clout, and financial support
2. Industry-sponsored senior design projects, with interdisciplinary student teams
3. Shared, inter-departmental facilities for hands-on learning in design and manufacturing
4. Cross-university course development and shared curricula in Product Realization
5. Student training classes in basic manufacturing skills
6. Early student exposure to hands-on engineering

Outcomes that were difficult to achieve:

1. Quantitative assessment of the educational benefits of this approach
2. Quantitative assessment of the benefits of working in concert with multiple universities
3. Video conferencing between faculty, students and industrial sponsors (higher cost, few benefits relative to audio conferencing)
4. Cross-university senior design projects (difficult to organize and manage, high risk of failure)
5. Professional quality, multimedia course materials (high cost and long development time are required for proper instructional development, and a publisher is needed)
6. Adequate resources to support large numbers of students (permanent funds and sufficient space)

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