

THE LEARNING FACTORY - A new approach to integrating design and manufacturing into the engineering curriculum

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Abstract

The *Learning Factory* is a new practice-based curriculum and physical facilities for product realization. Its goal is to provide an improved educational experience that emphasizes the interdependency of manufacturing and design in a business environment. The Learning Factory is the product of the Manufacturing Engineering Education Partnership (MEEP). This partnership is a unique collaboration of three major universities with strong engineering programs (Penn State, University of Puerto Rico-Mayagüez, University of Washington), a premier high-technology government laboratory (Sandia National Laboratories), over 100 corporate partners covering a wide spectrum of U.S. Industries, and the federal government that provided funding for this project through the ARPA Technology Reinvestment Program.

As a result of this initiative, over 14,000 square feet of *Learning Factory* facilities have been built or renovated across the partner schools. In the first two years of operation, the Learning Factories have served over 2600 students. Four new courses, and a revamped senior projects course which integrate manufacturing, design and business concerns and make use of these facilities have been instituted. These courses are an integral part of a new curriculum option in *Product Realization*. The courses were developed by a unique team approach and their materials are available electronically over the World Wide Web. Industry partners provide real-world problems and are the customers for students in our senior capstone design courses. As of December 1996, over 200 interdisciplinary projects have been completed across the three schools. These projects involve teams of students from Industrial, Mechanical, Electrical, Chemical Engineering and Business. Forty-three faculty members, across five time zones, are engaged in this effort.

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I. Introduction

A. The Need for Revitalizing Engineering Design Education:

The Learning Factory is the result of a desire to graduate better engineering professionals with technical competence in engineering science fundamentals as well as professional skills to effectively compete in today's market place. The Learning Factory is the result of listening to the stakeholders in the education process - students, faculty and industry. Our industrial partners tell us that they can no longer afford to put new employees through lengthy training or apprenticeship programs. Newly hired engineers must be able to contribute to the good of the corporation in a relatively short period of time. In order to do so, they must possess strong technical competence in engineering science fundamentals, as well as essential professional skills that enable them to effectively apply those fundamentals to solve real problems. Students want to improve their marketability. They are asking for the chance to develop ingenuity as well as analytical capability. They need to see applications as well as theory. Faculty want to be effective educators but need new resources and facilities to reap the benefits of active learning.

The Learning Factory recognizes the need for both intellectual and physical activities in order to anchor the knowledge and practice of engineering in the minds of students. While this approach is not really "new", it is part of the growing movement to reemphasize practice and hands-on experiences in engineering education. While the content of curricula, as well as the balance between theory and practice has dramatically changed over the decades [1], the predominant delivery method in most engineering schools today - the lecture - is relatively unchanged from that of a century ago. Lecture is a time honored, efficient technique for delivering large quantities of analytical information. In recent years, new findings in cognitive processes [2] and behavioral psychology [3] have demonstrated the limits of lecture, and alternatives to augment its effectiveness have been demonstrated [4], including laboratories and cooperative learning.

Lectures encourage passivity in students, leading them to expect the instructor to provide all required knowledge. Lectures are geared toward the verbal learner, and do not take into account the varied learning styles of our students. Many engineers are in reality "visual learners", much better served by active, visual and tactile teaching methods[5]. Many students who have the intelligence and creativity to be excellent engineers find little fulfillment or stimulation in the rigid confines of the lecture hall, and drop out of formal engineering programs as a result. They do not see the relevance of their required courses to the actual practice of engineering. Too often these are promising minority or female students, to whom this lack of relevance and stimulation is sometimes "the straw that breaks the camel's back". Just as one cannot learn to drive without getting behind the wheel; or to swim without getting wet; entry into the profession of engineering, particularly in the area of design, requires far more than sitting in a lecture hall.

The National Science Foundation has recognized the opportunities to improve engineering education and is providing impetus to change by sponsoring several major education initiatives and coalitions [6] including the partnership described in this paper.

B. A Short History of the Manufacturing Engineering Education Partnership:

The Manufacturing Engineering Education Partnership (MEEP) consists of Penn State, The University of Puerto Rico- Mayagüez, the University of Washington, Sandia National Labs, and more than 100 industrial affiliates. The partnership draws on the special strengths of each member and provides a unique opportunity to share physical and intellectual resources and explore diverse educational approaches. Students at these institutions come from a wide range

of geographic, socio-economic and cultural backgrounds. Together, these schools graduated 2,384 B.S. engineering professionals in the 1992-1993 academic year, all with the potential for significant impact on our nation's industrial competitiveness.

The MEEP partnership owes its existence and success to four factors:

1. Firm belief in the need for increased emphasis on practice in engineering education, particularly for engineering design
2. Ground breaking activities at Penn State and the University of Washington by the NSF ECSEL Coalition. [7]
3. The 1993 ARPA Technology Reinvestment Program (TRP) Solicitation [funding was provided from July 1, 1994 through June 30, 1997]
4. A common purpose and an unusual attitude of cooperation among the partners.

C. MEEP Objectives:

The specific objectives of our partnership are, to develop:

- 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;
- Outreach to other academic institutions, government and industry.

II. Combining Theory and Practice

A. New Curricula and Courses

Our curriculum is based on the direct linkage of theoretical studies with practice-based design and problem solving activities. **The Learning Factory**, in combination with the curriculum enables students to integrate design and manufacturing issues. Together, these developments are intended to produce an engineer ready for the 21st century, with the following qualities:

- Strong foundation in engineering science fundamentals;
- Well versed in the big picture of manufacturing and product realization, including the design process and business realities;
- Knowledgeable of current technologies and tools, and most importantly, their management and application to solve new problems;
- An effective team player;
- Adept at communication (oral, written, electronic); and
- Equipped and motivated for future learning.

This interdisciplinary curriculum, shown graphically in Figure 1, is available as a minor or a degree option at the participating universities. Several departments at each school are cooperating in this development, 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.

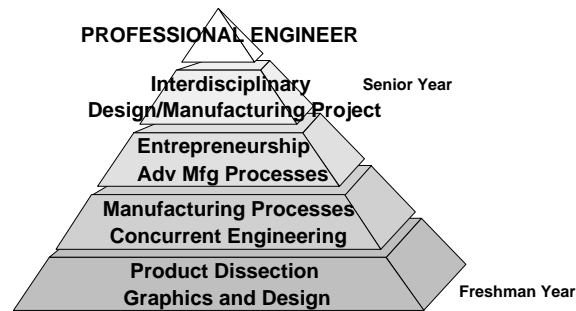


Figure 1. The product realization curriculum prepares students for productive careers in design, manufacturing and product realization

As part of the new curricula, several new courses have been developed across the partnership. In addition, a number of existing courses have been modified to take advantage of the Learning Factory concept. The courses developed by MEEP are described below.

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. This course is intended to complement engineering science and mathematics courses and to show students how these fundamentals relate to engineering practice. More information on this course can be found in reference [8].

2) *Concurrent Engineering:* This course presents the origin and meaning of the term *concurrent engineering* and discusses its role in modern engineering companies. Students gain an appreciation for the role of a 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. More information on this course can be found in reference [9].

3) *Technology Based Entrepreneurship:* This course is developed in conjunction with the School of Business and provides students with the fundamentals of entrepreneurship. 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 in the current TQM culture. 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. More information on this course can be found in reference [10].

5) *Interdisciplinary Senior Design Project:* This capstone course provides students with the opportunity to practice the design of products, processes and enterprises from conceptualization to actualization. Students work in interdisciplinary teams on open-ended hardware-oriented projects provided by our industry partners. This is a required course which existed previously, but under the auspices of this project, has been revised to include students from multiple engineering departments, working on industry projects.

The curriculum options at each of the universities are described below:

B. UPRM Certificate of Manufacturing

This certificate has been established in Industrial, Mechanical, Electrical and Chemical Engineering Departments. Basically, students utilize their technical and free electives to take 12-15 credits in manufacturing related courses. Six to nine credits are a common core based upon the courses developed by MEEP - product dissection, entrepreneurship and concurrent engineering- and the rest are credits that will support a student's development in technical and business aspects related to manufacturing. The certificate is administered by each department.

C. PSU Product Realization Minor

A 24 credit degree minor has been developed which is available to all engineering students. The minor consists of a coherent series of courses in Design and Graphics (3 credits), Product Dissection (3 credits), Manufacturing Processes (6 credits), Process Quality Engineering (3 credits), Concurrent Engineering (3 credits), Technology Based Entrepreneurship (3 credits) and Interdisciplinary Senior Design Projects (3 credits). The minor is administered by the Industrial and Manufacturing Systems Engineering Department. The MEEP courses may also be taken as technical electives by students not enrolled in the minor.

D. UW Product Realization Option

The Product Realization Option consists of: Introduction to Design (4 credits), Product Dissection (4 credits), Concurrent Engineering (4 credits), Statistical Quality Control (3 credits), Entrepreneurship (3 credits) and Capstone Design (variable, 4 to 8 credits). Other combinations of upper division, elective courses with the College of Engineering and the School of Business Administration can be used to provide other viable technical specialties.

E. Instructional Design Considerations

The MEEP curriculum builds on existing courses in graphics, design, and manufacturing processes. The instructional design emphasizes interactivity on two distinct levels. First, the courses are integrated into the students entire academic program, from introductory freshman courses to senior year design project experiences. In this manner, student-student, student-teacher, student-industrial partnering is fostered over the years, preparing the student for the leap from the classroom into industry. Second, the curriculum is much more than just lecture-based design. It incorporates case studies, problem based learning, guest lecturers from industry, active learning techniques, and interactive multimedia computer technologies in the classroom. Previously unavailable opportunities for hands-on engineering experience are provided in the Learning Factory.

The educational objectives of our curriculum, i.e. the desired skills which we want our students to develop, are listed in Table 1 as well as their level of integration into the MEEP courses. These skills were determined by our Industry Advisory Board and represent their view of the skills and capabilities which are required of the practicing engineering professional.

Table 1. Distribution of skills and knowledge through new courses

CURRICULUM THEMES	Product Dissection	Concurrent Engineering	Entrepreneurship	Process Quality Engineering	Senior Design Project
Engineering Science Fundamentals	P	P	P	P	P
Design/Synthesis	B	B	B	B	A
Probability Methods	N/A	N/A	N/A	A	A
Materials (Selection, Non-Traditional)	B	P	P	O	A
Creativity	B	O	B	O	A
Manufacturing Processes	O	P	P	O	A
Communication Skills	B	A	A	B	A
Team Skills	B	A	A	A	A
Problem Solving Skills	B	B	P	B	A
Total Quality	N/A	A	A	B	A
Business Concerns	O	B	A	O	A
Project Management	O	A	A	N/A	A
Cross-Disciplinary Industrial Projects	N/A	A	A	O	A
Environment and Societal Concerns	B	A	A	N/A	A
Integration of Product/Process	B	A	A	O	A

Legend: O=Overview B=Basic A=Advanced P=Prerequisite N/A=Not Applicable

F. Course Development Process

Curriculum and laboratory development are time consuming and costly processes. The partners are dedicated to the philosophy that sharing of resources and ideas, avoiding redundant efforts, utilization of new technologies for communication, and achieving consensus on curriculum content are critically important. Our mission was to jointly develop curriculum materials that are easily transportable and utilized among the MEEP partners, and exportable to the academic community at large. All course materials will be available either in textbook form, over the World Wide Web, or on a compact disk.

Course development consists of a four part process:

- 1) Planning - coordinators from each school agree on overall course objectives and content and how that course fits into the balance of the curriculum
- 2) Piloting - one school takes the lead role in developing the course specifics and offering it on a trial basis
- 3) Publication - The piloting school makes all course materials available in electronic format for use by other schools.
- 4) Deployment - The remaining schools apply the course materials and offer the courses, making whatever modifications are necessary to satisfy unique institutional requirements.

The development process is shared over the partnership as shown in Table 2. Communication and consensus-building were accomplished by regular face-to-face meetings (approximately two per year) and extensive use of electronic mail and teleconferencing. Each course development group included at least one undergraduate student, providing an indispensable "customer" viewpoint. The primary benefit of this collaborative approach was the elimination of redundant efforts at each school. For the price of developing just one or two

courses, each school now has four new courses to offer: Product Dissection, Concurrent Engineering, Process Quality Engineering and Entrepreneurship.

Table 2. Sharing of curriculum development efforts across the partnership

Course	Piloting Institution	Pilot Offering	Offering across MEEP	Export
Product Dissection	Penn State	August 94	Fall 95	Summer 96
Concurrent Engineering	Washington	September 94	Fall 95	Summer 96
Entrepreneurship	Puerto Rico	January 95	Fall 95	Summer 96
Process Quality Engineering	Penn State	January 95	Fall 95	Summer 96

III. The Learning Factory

Physical facilities for manufacturing and product realization, located at each partner institution, are the cornerstone of our efforts. Across our coalition, over 14,000 square feet of new and remodeled facilities, equipped with state-of-the-art equipment, are devoted to this activity. The Learning Factories at the three universities are illustrated in Figures 4-6. Each university has its own Learning Factory with basic capabilities including machine tools, work benches, 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.

The Learning Factory is an on-demand facility which 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 are used only sparsely during a typical academic week. 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.

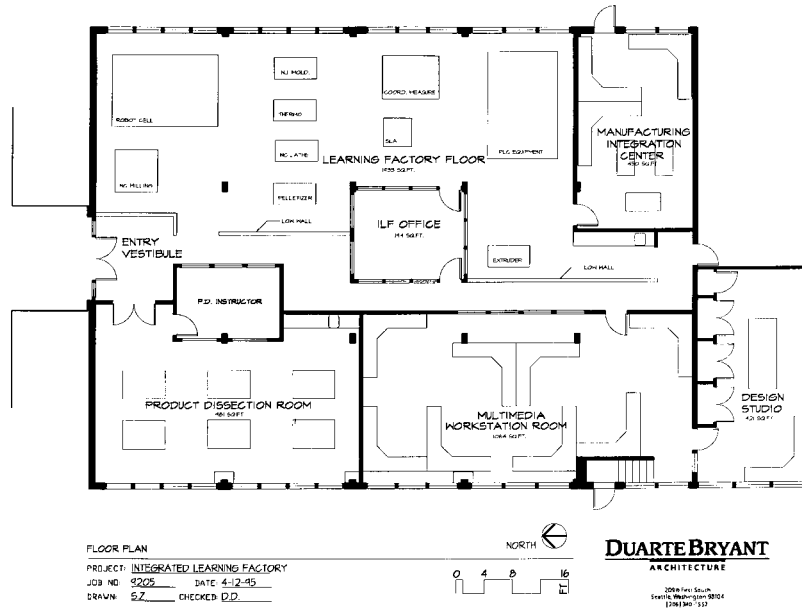


Figure 2. The learning factory at the University of Washington (6500 ft²)

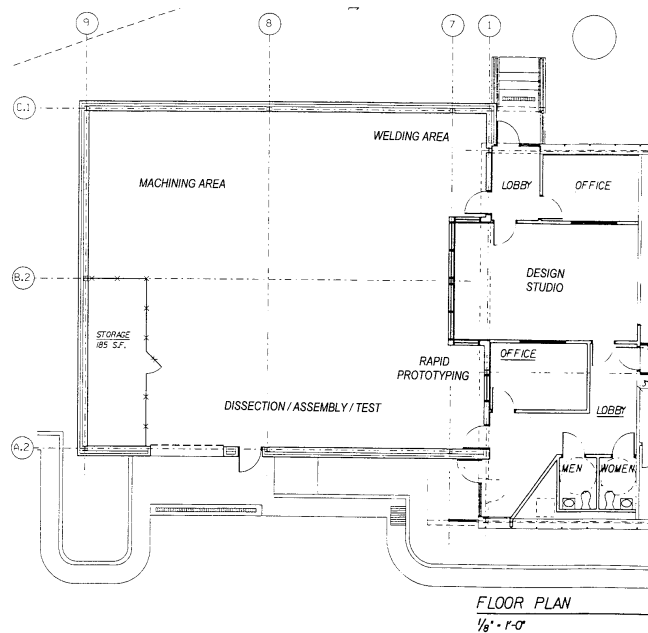


Figure 3. Penn State's learning factory (3500 ft²)

In the Learning Factory, students actively experience the product realization process in its entirety, from design concept to finished hardware. Our vision is a facility where students continually seek to implement their ideas, hone their skills and practice engineering in an environment similar to an industrial setting. We seek an experience where every academic term, students participate in a course that uses the Learning Factory as an integral part of its syllabus. For example, in the sophomore year, students in Product Dissection benchmark products, document designs using CAD equipment, perform measurements, critique manufacturing and design decisions and use prototyping facilities to implement their ideas for product improvement. Sophomores and Juniors are likely to be found honing their basic manufacturing process skills, and directly experiencing the interdependency of design and

manufacturing covered in Concurrent Engineering. Seniors in the design projects class work in cross-disciplinary product teams on a wide variety of projects requiring the use of advanced design and manufacturing concepts and facilities. The needs of our industrial affiliates are a prime source of these projects. Other projects revolve around student design competitions sponsored by the various professional societies (including SAE vehicle competitions), or student inventions resulting from the entrepreneurship class or independent studies.

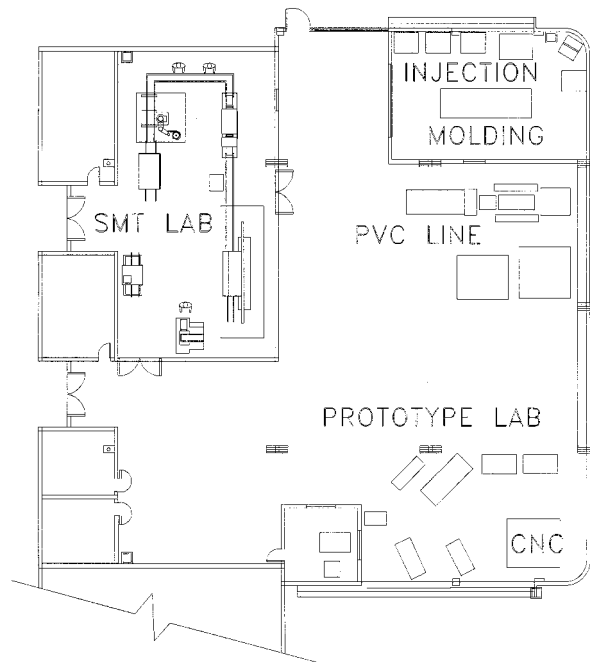


Figure 4. The learning factory at the University of Puerto Rico (4000 ft²)

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. Students naturally gravitate to these facilities and they provide a kind of home and social identity. A modern manufacturing facility, filled with busy students and on-going projects, is perhaps the most effective argument for convincing industry partners, recalcitrant faculty, and university administrators that engineering students need this and it must be supported.

IV. Industry Partnership

A critically important element in this operation is our Industry Partnership. Each university has a board of industry representatives who are convinced of the value of the Learning Factory and are volunteering their time to make this effort a success. They contribute their time, equipment, senior design projects and funds. The fact that these important people continue to donate their time is indicative of the merits of our activities and the benefits they perceive in this interaction.

One particularly successful model used at Penn State has been for this group to meet twice each semester to critique our efforts and offer strategic guidance. At the beginning of each semester, part of the meeting is devoted to a presentation of available senior design projects. Corporate sponsors meet with the seniors in our ME, IE and EE capstone design classes to present potential projects for the students to work on during that semester. This event gives

students the chance to network with potential employers, hear firsthand about what it is like to be a practicing engineer, and learn subtleties like professional dress and presentation skills. At the end of the semester, the same parties reconvene in the ballroom of a local hotel for the "Project Showcase". At that time, it becomes the students' turn to present their project results, via high quality posters and an oral presentation. The audience for this event consists of the industrial sponsors, students in all the senior design classes, faculty, students interested in Product Realization, the public and the news media. This event is one of our primary vehicles for marketing the Product Realization Minor to prospective students. It has also been very valuable in demonstrating the benefits of the Learning Factory concept to our faculty colleagues.

In order to be successful, this partnership must be mutually beneficial to industry and academia. Industry partners directly benefit from this partnership by:

- Availability of well-prepared engineering graduates who understand the product realization process;
- Opportunities to evaluate potential employees through internships, collaborative projects and classroom interactions;
- Direct assistance in product and process design problems through sponsorship of senior design projects;
- Professional development of industry personnel through teaching, learning factory and curriculum development;
- Technology transfer through Industrial-Academic exchanges - industry engineers in the classroom, and faculty internships in industry; and the
- Opportunity to influence and improve the education of engineers well into the next century.

The members of our industrial partnership span the spectrum from large multi-national corporations to small family-owned businesses. While a few large corporations (such as HP, GE, Boeing, GM) work with more than one university, most of these partners interact primarily with the university in their region. Represented industries include aerospace, automotive, electronics, pharmaceuticals, chemicals, computers, machine tools and consumer products. These industry partners have contributed over \$3M in cash and in-kind support for this project. The current industrial affiliates of this project are listed in Table 3.

Table 3. Industrial partners of MEEP

Abbot Labs	Accusort	Allegheny Valve
Allergan Medical	AMP	AT&T
Atotech	Avon	Baxter Biotech
Baxter Edwards	Bently Systems	Boehringer Labs
Boeing	Bristol Myers - Squibb	Caribe GE
Conair	Cutler Hammer	Dana Corp.
D/E Associates	DEC	DuPont
Eastman Kodak	ELDEC	ExtrudeHone
FF Industries	FLOW Int. Corp.	Fluke
Foundry Education Foundation	FORMOST	GBC Materials
General Electric Lighting	General Electric Ohio Lamp	General Instrument
General Motors	Globe Lift	Haleyville Mfg.
HealthTech	Henrob	Hewlett Packard
Holman Inc.	Hop Scotch Restaurant	IBM
Husky Injection	Industrial Dielectrics	Industrial Modernization Center
InFlow Inc.	Innoteck Inc.	Jack Ogle and Co.
JLG Industries	K2	Kennemetal

Kimberley Clark	Lifescan	Lutron
MARCO	Martin Consulting	Microsoft
Motorola	Muncy Machine Tool	Murata Electronics
New Holland	Northwest Pacific Fishing	Novatek
NYPRO	Olympia Orthotics and Prosthetics	PAC Northwest
PACCAR	Piezo Kinetics	Plastics Systems
Polymerland	Precision Components	PRECOR USA
PREMSCO	Procter and Gamble	Productos La Aguadillana
Professional Molding	Puerto Rico Manufacturers Assoc.	PR2000
PR Economic Development Adm.	Red Dot	Rolodex
SPE	Seafirst Bank	Security Plastics
Sensormatic	Stryker/Arroyo	Supertechnology
Taylor Packing	Techno-Plastics	Tektronix
Telecomm Solutions	Textron Lycoming	Upjohn
USDA Forest Service	Vasallo Paints & Coatings	Washington Technology Center
Wash. St. Recycle Assist. Program	Westinghouse	Wenzel and Associates
Xerox		

These partners contribute in several critical ways, providing physical and personnel resources including:

- Manufacturing/design student projects
- Practicing engineers in the classroom (guest lecturers, design project supervisors)
- Opportunities for faculty experiences in industry
- Donations and loans of equipment
- Direct financial support
- Summer student internships
- Expertise to develop Learning Factory facilities
- Tours of industrial facilities for students and faculty
- Assistance with course development (such as case histories)
- Feedback on MEEP curriculum developments
- Strategic guidance in matters of fund-raising and management

V. Outreach

The MEEP partnership is dedicated to changing engineering education and ensuring that the benefits of those changes are available to all students. Our approach will attract outstanding students who wish to supplement the traditional lecture environment with real-world experiences in the Learning Factory. The approach will also help retain those students who are not stimulated by the traditional lecture environment, but who have the intellectual and creative abilities to become exceptional engineers. Our curriculum materials are modular, transportable and available to the academic community at large. Extensive use is made of electronic techniques for communication and curriculum export, such as multi-media computer tools, the World Wide Web, and video conferencing. Our outreach activities are coordinated by colleagues at Sandia National Laboratories.

Portability of curriculum across platform, editability of files by faculty, and accessibility of files over the Internet were key considerations for the outreach activity. Ease of access issues are continually being addressed. For example, a style guide with a template for format issues is shared among authors to ensure that files may be imported and printed without difficulty on any platform. Consistency of presentation was a minor problem eradicated by the implementation of a style guide, enabling authors to employ the same font, format, point size,

and Microsoft Powerpoint template, for a coherent look and feel of all materials developed by the partnership. Commercial publishers are currently being contacted to take the next step and convert the course materials into professional quality, well documented, stand alone products.

The outreach goals evolved over the project duration. Early in the curriculum development phase, outreach within the participating universities was paramount, now, two years into the project, outreach beyond the three universities is critical. Initially, files were shared via file transfer protocol (ftp) at anonymous ftp sites at the University of Washington and at Penn State. A limited number of CD-ROMs were issued containing course notes and lecture materials in Microsoft Word and Powerpoint files. Multimedia elements were developed using Authorware software (by Macromedia Inc.), in part because of the power, ease of construction, and portability to either MAC or PC platforms. Finally, a site was developed on the World Wide Web to advertise the availability of the curriculum and to demonstrate highlights of the learning factory approach to the engineering community at large (<http://lfserver.lf.psu.edu>). Other information is also on the web site, including course materials, real-time video images of the Learning Factory, descriptions of curricula, summaries of completed industry projects, information on how to sponsor a senior design project, descriptions of courses, publications, listing of current events, and schedules for training courses.

VI. Impact and Assessment

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. From the industry perspective, we finally have a concept (the Learning Factory) that they understand, appreciate and wholly embrace as more fully meeting their needs. Their enthusiasm has translated into the beginning of change in the attitudes of faculty members - that a hands-on educational environment, in concert with engineering science, is a valid approach. Specific accomplishments of this program at the three universities are described below. These accomplishments illustrate the richness and diversity of the coalition approach and attest to the cross-fertilization engendered by this partnership. An additional benefit of the coalition approach, with strong industry support, is to markedly increase the stature of this project at our individual campuses. In November 1996, this project was awarded an honorable mention for curriculum innovation by the American Society of Mechanical Engineers.

A. Penn State Accomplishments

The Learning Factory project at Penn State can boast of several major achievements:

- Four new MEEP-developed courses have been instituted at Penn State (Product Dissection, Concurrent Engineering, Entrepreneurship, Process Quality Engineering)
- Ten existing courses have taken advantage of the Learning Factory facilities. (IE328 Production Engineering, EE438 Antenna Engineering, EE403W Electronic Design, ME415W Senior Design Project, ME414W Thermal Design, IE430 Industrial Projects, ME456 Robotics, ME452 Vehicle Dynamics, ENGR297 Enigmatic Engines)
- 65 industry-sponsored interdisciplinary senior design projects have been completed. Typically 15-20 projects are executed each semester. Companies contribute a small fee (\$1000 per student team) to cover incidental project expenses and Learning Factory overhead.
- A new 3,500 square foot Learning Factory facility has been built, equipped, and staffed. It is open 70 hours per week for students in all engineering departments.

- 33 industry partners have contributed projects, support and supervision.
- Over 900 students from 5 engineering departments have used the Learning Factory in their courses or projects during the last year.
- Training courses (non-credit, free, voluntary) are offered in safety, basic machining, welding, and CAD and are a prerequisite for students to use the Learning Factory facilities. Approximately 120 students take these courses each semester.
- The minor in *Product Realization* has been developed, approved and instituted by the university
- We have instituted the "Project Showcase", a trade show type event, at the end of each semester to present student design projects to the general public and to facilitate industry-student interactions.
- Three faculty who were heavily involved in MEEP course development received promotion and tenure while working on this project.
- The project team has received a highly competitive *PSU Provost's Award for Collaborative Instruction and Curricular Innovation*.
- Our efforts were featured in an article in the New York Times, Education Life Magazine on April 2, 1995 [11].

B. University of Washington Accomplishments

A new curriculum option in Product and Process Realization has been developed. It consists of a set of core design and manufacturing related courses plus technical electives that will complete the 'option'. In this core the entering student will initially progress through a series of 'skill' related courses. The freshman year will start with Engineering 100 Introduction to Engineering Design. Upon entry into the ME program, typically in the Sophomore year, she/he will progress throughout the sequence of ME 123 Engineering Graphics to learn how to communicate their design ideas graphically through sketches and CAD, and further enhance their design activities in ME 295 Product Dissection.

The Junior year is devoted to integration of design and manufacturing knowledge. ME 304 Manufacturing Process gives the students the basics of manufacturing principles and material selection with hands on experience in the various processes. In ME 395 Introduction to (Product) Design, we extend the idea of product dissection with the introduction of Product Benchmarking as a means to teach product and process design. ME 352, Mechanical Systems Design, is devoted to the details of system component design. In the senior year, students will take ME 495 Capstone Design plus and additional ME 499 Independent Study to provide a two to three quarter sequence of Industrial Projects. In addition they will be able to select 8 to 12 credits of technical electives. These could include Finite Element Analysis, Advanced Manufacturing Process, Concurrent Engineering, or Technology Base Entrepreneurship. In all these courses we envision a vigorous interplay between classroom lectures, design, analysis, hardware implementation, demonstrations, and/or dissections in the Learning Factory.

After 24 months (8 quarters) of operation we can claim the following accomplishments at the University of Washington:

- A total of 1067 students have been involved in MEEP related courses and activities
- A new curriculum with a pathway (or option) in Product Realization has been adopted by Industrial and Mechanical Engineering. In 1996/97 academic year we have 35 ME students involved.

- New courses in Product Dissection, Concurrent Engineering, Entrepreneurship, and Process Quality Engineering are now offered regularly, cross-listed and co-taught by several departments.
- The Learning Factory, with 6,500 square feet of renovated space and upgraded equipment, is fully operational as of the summer of 1996.
- Twenty-five industry and university (related to research in rehabilitation medicine, forestry and biomechanics) sponsored senior capstone design projects have been executed by IE and ME students.
- Student entries and participation into national competitions such as the SAE Formula Vehicle, the ASME Human Powered Submarine, and the RAVEN Human Powered Plane are now a major part of the students' professional development.
- A paradigm shift in instructional attitudes among both the faculty and students is taking place. Courses are co-taught by faculty and industry participants. In the classroom collaborative learning, with students working effectively in teams, is now a reality.
- Approximately 1/3 (8 faculty) of the ME faculty has formed a new Design Group to carry out joint teaching and research efforts in Products and Processes Realization. We hope this will become an interdisciplinary design group.
- Faculty from the University of Washington, Washington State University and Tacoma Community College are jointly participating in a NSF sponsored program to extend the products and processes related curriculum developments at the entry level (freshman and sophomore) to the community college system.

C. University of Puerto Rico-Mayagüez (UPRM) Accomplishments

The MEEP initiative has had a tremendous impact at the University of Puerto Rico-Mayagüez. More than 1000 students have been positively affected by their participation in course work, Learning Factory, industry based projects and interaction with other students at participating universities. Over 160 industry based projects are being coordinated during the academic year and we have had an industrial based sponsorship exceeding \$2,000,000 of cash and in-kind contributions from more than 60 industrial sponsors.

Currently there are five disciplines participating in this effort at UPRM: Industrial, Mechanical, Electrical and Chemical Engineering and Business Administration. There is a Certificate in Manufacturing for each engineering discipline which basically consists of 4 to 5 courses. Students are oriented to take the following MEEP courses as a core: Product Dissection, Technology Based Entrepreneurship and Concurrent Engineering. Product dissection is coordinated and offered by Mechanical Engineering, Technology Based Entrepreneurship is coordinated and offered by the College of Business and Concurrent Engineering is coordinated and offered by the Department of Industrial Engineering. Typically about 75-80 students are enrolled in these three courses. In Technology Based Entrepreneurship students develop innovative ideas of a potential marketable product. This has been conducted in coordination with Penn State and the University of Washington. At UPRM these potential products are given to the students in Concurrent Engineering to apply the design methodology, redesign and refine products, develop prototypes and demonstrate the manufacturing and business potential. The entrepreneurial spirit that has been developed is of major relevance to the economy of Puerto Rico. It is important to highlight that these three courses are team taught. In Product Dissection and Concurrent Engineering, three faculty members participate in lecturing and about eight faculty members do the same in

Entrepreneurship. More than 20 faculty members that participate in the MEEP effort. This participation ranges from technical advice on projects to coordination and course delivery.

To complete the requirements for the Certificate students take other courses related to manufacturing aspects of major interest to them and to industry plus the courses already required in their departmental curriculum. For example, IE students may take courses in manufacturing simulation, robotics and automation or product design. Electrical, Chemical and Mechanical Engineering majors may take some of those courses plus courses that are required for Industrial Engineering majors, but are electives for them. Examples of these are applied statistics, quality control, manufacturing process, and plastics engineering.

Currently about 85 students are in these paths, and the interest is growing rapidly. The core "MEEP courses" are offered every semester, although this may change. For the most part students are involved in Capstone Projects that are practice-based, performed in industrial settings, teamwork oriented and heavily emphasize the use of written and oral communication skills. About 85 projects are administered each semester and this is in a growing mode, since Chemical and Electrical Engineering are expanding their efforts in this regard. These industrial based projects have academic and industrial advisors as part of the working team.

In addition various initiatives have been developed with the Colleges of Arts and Sciences and Agricultural Sciences. Students are carrying out interdisciplinary projects to stimulate entrepreneurial developments and faculty involved in the MEEP courses are serving as mentors to course developments in science which emphasize more industrial practice and entrepreneurship. During the first year a student exchange was established with PSU which is being expanded to include UW and Sandia.

The creation and expansion of the Learning Factory has provided a more attractive environment for students and faculty and has stimulated undergraduate and graduate research activities. Industry-based research projects have been developed to help small businesses with product development. We instituted a semester fair in Entrepreneurial Development, focusing on product design, with the participation of more than 20 teams of students. An extension of these efforts is the development of an Incubator Program with the Economic Development Administration of Puerto Rico.

These accomplishments have been possible to a major extent, because of the existence of this partnership. The visibility obtained plus the opportunities provided to students, faculty and industrial sponsors has allowed us to develop a more comprehensive approach of enhancing the educational process. Moreover, it has permitted every participant to become exposed to a more interdisciplinary environment, that is not only applicable to manufacturing, but to the learning/teaching process as a whole. This by itself constitutes a significant change in the culture and has helped to institutionalize our efforts.

D. Assessment

A formal assessment of the project outcomes and deliverables is underway and is a requirement of the ARPA project monitor. Students, faculty and industry participants are being queried. The assessment methodology has the following elements:

- internal (self-assessment)
- external (outside the partnership)
- multiple criteria (variety of modes and viewpoints)
- holistic (integrated)
- qualitative and quantitative components

Detailed assessment results will be reported in a future paper.

VII. Future Challenges and Opportunities

The major challenge and opportunity now facing MEEP is to continue these activities after the federal funding has expired. Each institution is in the process of establishing permanent funding mechanisms to support future operations. These funds will come from a mixture of university and industry sources. Additional challenges include: broadening participation to include more engineering and business departments; marketing and continuous quality improvement of the Product Realization courses; disseminating curriculum materials to interested universities; convincing faculty colleagues of the scholarly content of educational activities; and expanding the base of industry partners in order to insure that these efforts continue to meet the needs of US. Industry.

VIII. Conclusions

A unique partnership of universities, industries, and the federal government has been formed to integrate design, manufacturing and business realities into engineering education. This partnership has developed an integrated curriculum and physical facilities for product realization at each university, with the cooperation and assistance of over 100 industrial partners. The primary products and benefits of this coalition to students, industry and faculty are:

- superior engineering graduates who are well prepared to impact overall business productivity;
- a new paradigm for engineering education based on a balance among analysis, design, processing, and integration;
- practice-oriented teaching modules, available electronically (at WWW address <http://lfserver.lf.psu.edu>);
- and greater prestige for manufacturing and design education in university curricula.

The things that worked well and which are recommended practices include:

1. Cross-university course development process and sharing of course materials
2. Industry advisory boards for strategic guidance, political clout, and financial support
3. Industry sponsored senior design projects
4. Modern facilities for product realization (i.e. the Learning Factory)
5. Student participation in course development
6. Use of the World Wide Web for information dissemination
7. Student training classes in basic manufacturing skills
8. Integrated curricula in Product Realization

Some items that were difficult to achieve include:

1. Quantitative assessment of the educational benefits of this approach (the subject of a future publication)
2. Quantitative assessment of the benefits of working in concert with multiple universities
3. PictureTel video conferencing between students, and faculty (higher cost, few benefits relative to audio conferencing)
4. Cross-university senior design projects (difficult to organize, high risk of failure)
5. Professional quality, self standing course materials (high cost and long development time are required for proper instructional development, and a publisher is needed)

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Biographical Information

John S. Lamancusa, Co-Principal Investigator for Penn State, is an associate professor in mechanical engineering. Before coming to Penn State in 1984, he was employed at AT&T Bell Laboratories where his technical responsibilities included electronic packaging, product design for automation and acoustic design of business telecommunications equipment. He received his Ph.D. in mechanical engineering, with a minor in electrical and computer engineering, from the University of Wisconsin-Madison in 1982. Dr. Lamancusa earned his B.S. in mechanical engineering from the University of Dayton in 1978. His areas of academic research and industrial consulting include mechanical design and design optimization, design for manufacture, noise and vibration control, musical acoustics and mechatronics.

Jens Jorgensen, Co-Principal for the University of Washington, has served as a University of Washington faculty member since receiving his Ph.D. in mechanical engineering from MIT in 1969. His area of specialization is design and control of dynamic systems, with a concentration on manufacturing systems. His extensive collaborations with industry and government agencies include work for Weyerhaeuser, Boeing, and the USDA Forest Service. He helped to establish the Manufacturing Systems Center of the Washington Technology Center and was its director from 1983 to 1990. He has been actively involved in teaching undergraduate students for 33 years. He was the UW principal investigator for the NSF sponsored ECSEL coalition that initiated a new paradigm in the teaching of design and practice based engineering. In 1993 he received the "Academic Engineer of the Year" from the Puget Sound Engineering Council.

José L. Zayas-Castro, Co-PI for the University of Puerto Rico - Mayagüez, has a B.S. degree in Industrial Engineering from UPR-Mayagüez (1978), and M.S. in Industrial Engineering (1979), MBA (1981), and Ph.D. in Management (1983) from Rensselaer Polytechnic Institute. Dr. Zayas conducts research and consulting in statistical process control, productivity improvement, information flow and office automation, manufacturing and business strategy, manufacturing and business strategy, economic and cost analysis, manufacturing simulation, and general management. He is a professor in the Industrial Engineering Department, for which he served as department head between 1987 and 1990. He is the director of the IE microcomputing center, co-coordinator of the Manufacturing Laboratory, and directs the Institute for Innovation in Manufacturing.