Teaching Lean Process Design using a Discovery Approach

Sharon A. Johnson, Arthur Gerstenfeld, Amy Z. Zeng,
Boris Ramos, Saumitra Mishra

Department of Management
Worcester Polytechnic Institute
Worcester, MA 01609

Introduction

Operations and industrial engineering practice have been transformed over the past 20 years by the principles of lean thinking. Womack and Jones [15] describe lean thinking as an antidote to *muda*, meaning waste. Lean thinking helps to create a value stream throughout the supply chain by eliminating waste. Lean design is guided by general principles, which are translated into practice using tactics such as creating manufacturing cells. The design process is complicated because in reality not all waste can be eliminated, particularly in complex processes that extend across organizational boundaries. To be effective designers, students need to understand how variability affects process dynamics and to combine this knowledge with analysis of process data.

In this paper, we describe lean laboratory exercises that we developed based on a physical simulation of a clock assembly called TIME WISE. Students taking an introductory course in production system design are required to take the laboratory, which meets weekly for 2.5 hours. Traditional topics covered in the course are linked through the lean concepts of value, flow, demand pull and perfection. The physical simulation that serves as the basis of the lab was developed by MEP-MSI and is used by Manufacturing Extension Partnership (MEP) programs in several states to teach lean principles to employees at small- to medium-size manufacturers. In adopting the simulation to an undergraduate course, we wanted to provide students with more opportunity to 'discover' theory, by generating and analyzing data that could be used to support decision-making. The laboratory exercises specifically address: (1) 'traditional' manufacturing processes and process variability, (2) problem-solving using a QI-story format, (3) process flow, takt time, and balance, (4) demand pull and visual management, (5) supply chain management, and (6) product customization.

We have offered the laboratory sessions once at Worcester Polytechnic Institute (WPI), and report here on our initial analysis of the teaching experience and student learning. Our objectives were: (1) to develop students' ability to apply lean design principles, (2) to develop students' ability to analyze data, and (3) to increase student understanding of fundamental process dynamics and variability. We used student surveys and an evaluation of student work to assess our success in meeting these objectives. In this paper, we concentrate on the impact on our first objective, the ability to apply lean principles.

Literature Review

Many organizations are focusing on streamlining their supply chains to increase responsiveness, and there is a need for analysts and engineers to improve such processes. Supply chains have many stages, often involving different firms, which require coordination and synchronization [10]. To be effective designers, students need exposure to research and practice in applying lean concepts in complex environments, where design is more difficult. In developing our approach, we examined how lean principles were taught in a number of settings and reviewed pedagogical approaches.

Teaching Process Design and Lean Principles. We reviewed courses taught in IE programs at a number of universities and found that relatively few had developed a separate course focusing on with lean topics at the undergraduate level. Those that had lean courses typically geared these courses to upper-level undergraduates or graduate students. More typically, courses had been revised to address the individual tactics associated with lean design, but typically as an add-on topic (for example, in production planning and control, one might add a session on kanban). We had traditionally taken this approach at WPI. As a consequence, we observed in senior projects that students often could not articulate the underlying principles of lean design (at least initially), and they failed to understand the links between various tactics and the conditions necessary for their success.

We also examined the Introduction to Industrial Engineering courses at a number of schools. Many schools have created such introductory courses in the engineering disciplines to reduce attrition rates by linking traditional mathematics and science topics to applications [1]. While such courses in IE have provided an effective overview of the discipline, course materials and textbooks do not focus on process design or the impact of lean ideas (see, for example, [14]). As with lean topics, project-based courses that focus on process design are generally aimed at senior-level students (see, for example, [9]).

On the other hand, many universities have established partnerships with industry to teach and apply lean ideas. For example, Kettering University has established a lean manufacturing program in conjunction with Ford Motor Company [11]. Students focus on planning, analyzing and implementing lean principles, gain professional experience and apply lean principles by working on opportunities provided by Ford Motor Company and its partners. Georgia Tech has established Georgia Teach Lean Enterprise Services, which conducts day- or week-long programs to impart lean ideas to industry [8]. Rochester Institute of Technology (RIT) has a Center for Excellence in Lean Enterprise (CELE) [12]. Both of these Universities use classroom training supplemented with hands-on applications, plant floor exercises, and live simulations. The continued interest in and success of such partnerships provides evidence that the ability to apply lean topics is important to industry. We can also take advantage of the methods and materials used in these settings for undergraduate teaching.

Discovery Learning. "What we have to learn to do, we learn by doing." [2]. Evidence suggests that students' design and problem-solving abilities are improved in courses that use active and collaborative learning [13]. The lean laboratory exercises we describe in this paper were designed to engage students in their learning, setting the high expectations, cooperation and faculty/student interaction consistent with good practice in undergraduate education [5]. Discovery learning seeks to connect students to knowledge. In this approach tools and information may be provided by the faculty to solve the problem, but it is the responsibility of students to "make sense" of them by drawing conclusions based on his/her own experience and knowledge.

As described by Bicknell- Holmes and Hoffman [3], there are five basic methods associated with discovery learning. Case-based learning is the most common and easiest method to apply. In this active learning strategy, students learn through stories that illustrate the effective application of knowledge, skills or principles. Incidental learning is an active learning strategy where course content is tied to game-like activities; here, knowledge is gained indirectly. In learning by exploring methods, students ask a faculty member or other students about a particular topic or skill. The faculty member tries to direct the interaction in a particular conversation or a topic. Learning by reflection is an approach in which students apply higher-level cognitive skills, focusing on deeper levels of comprehension and analysis. In simulation-based learning, an artificial environment that is close to the real environment is created so that students have the advantage of developing and practicing complex set of skills. Our approach to discovery-based learning primarily combines two methods – learning by exploring and simulation-based learning.

Lean Design Laboratory Exercises

Because lean thinking plays a central role in process planning in most organizations today, we believe that students should be given a holistic view of lean principles early in their academic careers. The goal of this project in our IE curriculum was to provide a process design foundation early, embedded in the contemporary business context that includes lean ideas. Project-based courses that build repeatedly on core ideas in a 'spiral curriculum' have been successfully implemented in other engineering disciplines at WPI ([6],[7]). We thus established the lean laboratory exercises as part of an introductory operations and industrial engineering course, currently titled "Production System Design". Industrial engineering majors take this course early in their program, and it serves as a foundation for more advanced courses. The course is also taken by management majors at WPI to fulfill their operations management requirement, as well as students in related engineering disciplines such as manufacturing and mechanical engineering. For these students, it may be the only operations and industrial engineering course that they take.

Laboratory Format and Topics. We created laboratory exercises using the TIME WISE simulation developed by MEP-MSI, which is used by the Massachusetts Manufacturing Extension Partnership (MEP) to teach lean principles and tactics. In this simulation, students assemble two types of clocks, using a 4-stage process. In addition to assembly personnel, the simulation requires production planners, material handlers, quality inspectors, warehouse clerks, and inspectors. The simulation is carried out in a large group, with each group member assigned a different role. One simulation takes 15 minutes, and corresponds to a work shift. We ran two sections of the lab with 15 and 18 students respectively.

The Massachusetts MEP uses TIME WISE as part of one-day seminars that provide a foundation for understanding the principles of lean manufacturing. Employees of small- to medium-size firms attend the seminars. There are two major differences between our laboratory sessions and the seminars conducted by MEP that required some adaptation of TIME WISE. First, participants in MEP seminars typically have been working for several years, often many years. They bring to the seminar an understanding of manufacturing operations, and can tie what they learn to their own work context. Students taking introductory course at WPI are usually sophomores and juniors, who typically have little work experience in engineering or operations (they are more likely to have worked service industries, including retail, restaurants, and computer services). The TIME WISE simulation provides them with a context for exploring lean principles, but we need to spend more time understanding basic process dynamics and relating issues to other examples. Second, we have significantly more time available (approximately 15 hours of lab time versus about 4 hours spent on TIME WISE in MEP seminars). With this additional time, we ask students to collect data on the process and use more structured methodologies (e.g., assembly line balancing) to suggest solutions. We also explore problem-solving approaches, and experiment with proposed solutions to see how well they work. Finally, we explore additional scenarios to examine the impacts of product customization and distant suppliers.

An overview of each laboratory session is provided in Table 1. Each lab lasted approximately 2.5 hours and was focused on a particular topic. The format of the labs was similar. Using data collected from previous labs (e.g., lead time, work in progress, quality data), students were asked to propose solutions for continuous improvement using tools introduced in class. For example, in session 3, one focus of the lab is better balance among the various assembly tasks. In the course lectures, students have reviewed assembly line balancing and now have an opportunity to apply it. After students present one or more solutions, we then set up the lab to experiment and see what improvements can be made to the solution. In our first delivery of the course, we explored supply chain ideas in another simulation but will be switching to the TIME WISE activity outlined in Table 1 for future courses. Because undergraduate courses are delivered in a 7-week format at WPI, students completed an in-class laboratory for session #6 that required no additional assignment outside of class time. By the end of the term, students were focusing on an exam and a project as part of the course.

An Example of Student Work. In Session #3, students examined the issues of flow and balance, and the impact on process performance. Using the 7-step problem-solving approach [4] introduced in Session #2, students were asked to explore the root causes of the long lead times experienced in the first laboratory session (with the original layout). Given data on customer orders, students could calculate the takt time needed to meet demand, i.e.,

$$Takt\ Time = \frac{15\,\text{min}\ per\ shift}{(90\,orders\,/\,5\,clocks\ per\ batch)} = 0.83\,\text{min}/\,batch\quad or\quad 10\,\text{sec}/\,clock$$

Given assembly times (captured by students playing industrial engineers in earlier sessions), students could also estimate capacity to find bottlenecks. Using assembly line balancing ideas, students could then explore new ways to assemble clocks to achieve takt time. Students suggested combining assembly operations in different ways and shifting labor resources to improve capacity. In experimenting with the proposed solutions, students learned why it is important to have good data and capacity cushions. Although the solution we tested in the lab worked well on paper, variability in the actual assembly times kept students from achieving the desired production rate (although it was much improved from Session #1).

Table 1: Lean Laboratory Exercises

Session and Topic	Description	Lab Assignment
Session #1: Traditional Process	• Traditional process includes large lot sizes, unbalanced and insufficient capacity, poor layout • Played for 3 shifts, switching roles so students could observe the process from several viewpoints	• Calculate and summarize performance measures, including lead time, capacity, quality • Identify process problems
Session #2 Problem-Solving	• Introduce 7 step problem solving method developed by Center for Quality Management to examine TIME WISE process • Examine process variability and capability	• Use the 7 step method to define a root cause and improvements that can be made to TIME WISE
Session #3: Balance and Flow	• Revise TIME WISE setup to reflect student suggestions • Measure process performance and suggest additional improvements	• Calculate takt time • Balance work and capacity to achieve takt time • Simplify flow
Session #4: Demand Pull and Perfection	• Introduce additional product to examine robustness • Revise TIME WISE setup to reflect student suggestions, test kanban and visual management • Measure process performance and suggest additional improvements	• Develop a demand pull system • Suggest visual controls and 5S activities
Session #5: Supply Chain	• Examine the impact of distance and variability in the supply chain on system performance	
Session #6: Product Customization	• Introduce customized products • Explore the advantages of a postponement strategy	

In the 7-step problem-solving approach, students develop a QI story to document the problem and solutions. Figure 1 shows a student representation of the original scrambled flow in the TIME WISE process (as experienced in Session #1), used to demonstrate pictorially the flow problem. One of the student groups came up with the idea of separate lines for the two different products, as shown in Figure 2. Focusing on specialization worked quite well for the two product lines but as we moved into Session #4, a new product was introduced. Students discovered *(learning by exploring)* that the solution worked well for one problem but when the process complexity and variability were increased, the solution required modification.

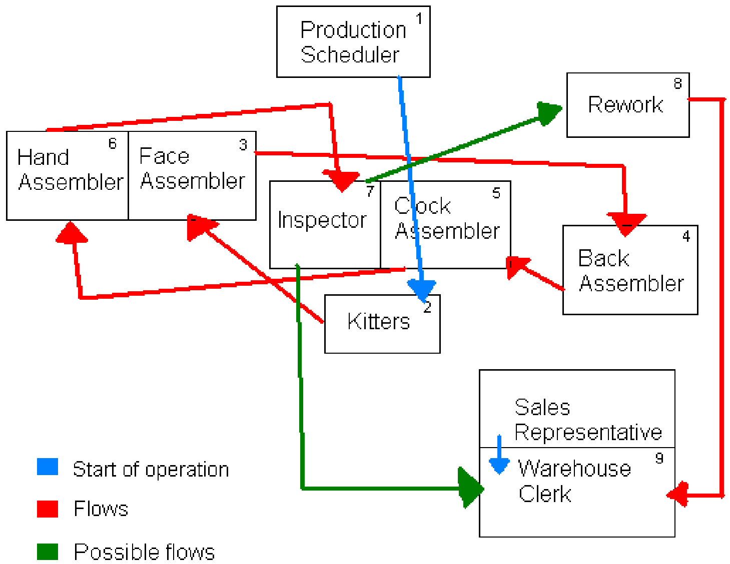

Figure 1: Process Flow in Lab Session #1

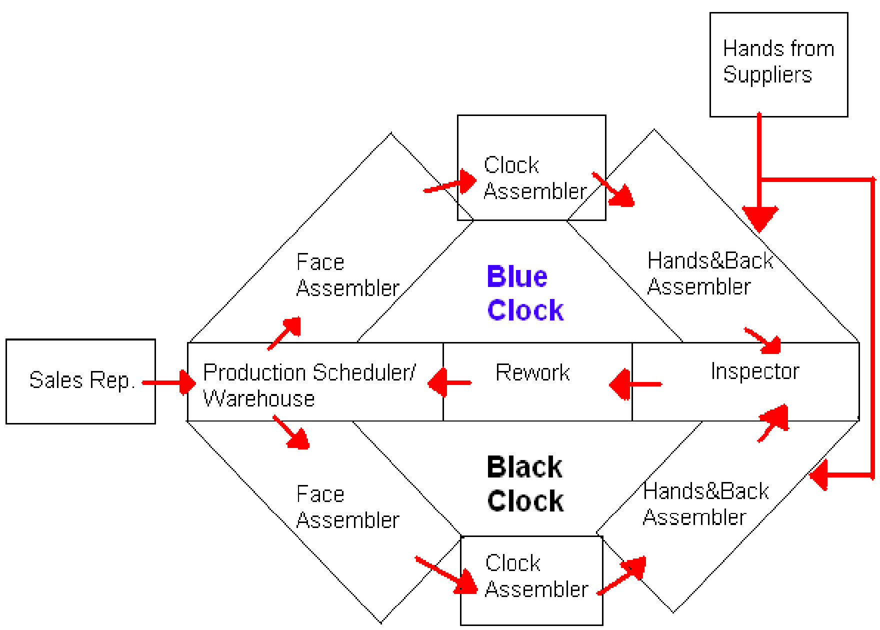

Figure 2: Specialized Lines in Lab Session #3

Project Results

Our objectives in introducing the lean laboratory exercises were to improve students' ability to apply lean concepts, to improve students' ability to use data to support decision-making, and to improve student understanding of process variability and dynamics. We are using student surveys, course evaluations and reviews of student work to establish our success in achieving these objectives. Data was collected from a course section taught in Spring 2002 without the laboratory sessions to compare to our first use of the sessions in Fall 2002. We have started our data analysis, and report preliminary results for the first objective in this paper.

Results from Student Surveys. We used student surveys to examine student confidence in their learning in a variety of areas, including their understanding of lean principles, supply chain activities, and calculation and understanding of process measures. We gathered data at the beginning and end of each course. In general, students expressed greater confidence about their knowledge with the introduction of the laboratory exercises, particularly in their ability to understand and apply lean concepts. Figure 3 shows student responses regarding their understanding of lean thinking and its application. In the Fall 2002 course with the lab sessions, 93% of students indicated that they understood all lean thinking principles and their application at the end of the course. Only 5% of students in the Spring 2002 course with no lab sessions expressed this level of confidence.

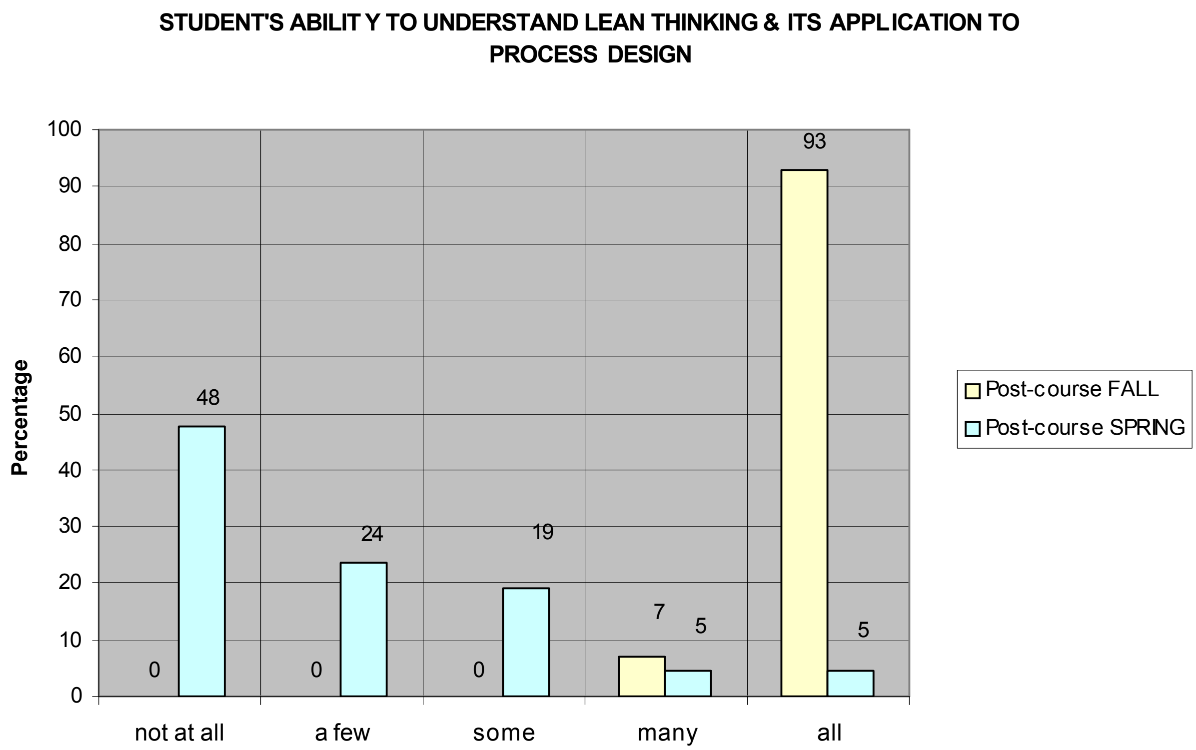

Figure 3: Students' Confidence in their Ability to Understand Lean Thinking and its Application.

Students also evaluated their ability to understand a variety of process measures and to calculate them. As shown in Figure 4, students taking the course in either the Spring (without the lab exercises) and the Fall (with the lab exercises) felt confident in their understanding of process measures. Students in the Fall session, however, expressed significantly more confidence in their ability to calculate process measures relative to the Spring.

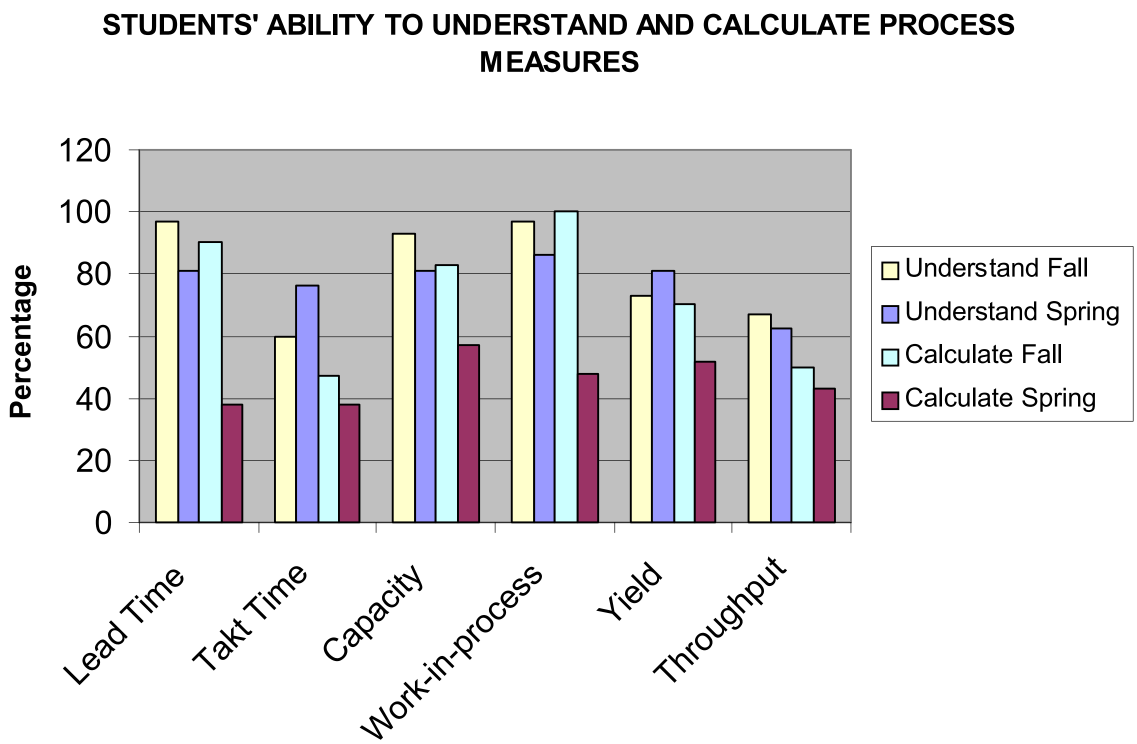

Figure 4: Students' Confidence in their Ability to Understand and Calculate Process Measures

Results from the Evaluation of Student Work. In addition to student surveys, we collected student responses to essay questions on exams and have started evaluating them in relation to our objectives. We broke each objective into smaller aspects, then created rubrics to score student work relative to that aspect of the objective. Table 2 shows rubrics we have developed to evaluate students' ability to understand and apply lean ideas. Currently, these rubrics have been applied to a subset of final exams given in Spring term (without the lab) and in Fall term (with the lab).

Our evaluation of students' ability to apply lean ideas based on their work in final exams was virtually unchanged between the Spring and Fall terms, based on these rubrics. We were surprised by these results, but have several hypotheses that we are testing as we move forward. First, the final exam in the Spring term was a take-home exam, where students were expected to

Table 2: Rubrics for Scoring Students' Ability to Apply Lean Design Principles

Objective Aspect	5 EXCELLENT	4 VERY GOOD	3 GOOD	2 FAIR	1 POOR
Students understand lean thinking principles and can apply them in specific settings.	Students can apply all principles of lean thinking: • Value • Flow • Pull • Perfection giving clear definitions of their meaning and/or give examples of their applications on specific cases.	Students can apply three principles of lean thinking giving definitions of their meaning and/or give examples for the application of these three principles.	Students can apply two principles of lean thinking, giving definitions of their meaning and/or give examples for the application of these two principles.	Students can barely apply one principle of lean thinking, giving definition of its meaning and/or give examples for the application of this principle.	Students cannot apply any principles of lean thinking in any case.
Students comprehend the links between various lean tactics	Students are able to fully identify 7 tactics in a given ordering scheme and/or explain the logic of its sequence	Students can satisfactorily identify a of given ordering schemes, identifying the correct order of five tactics and/or explaining the logic of its sequence.	Students can partially identify one of the existing ordering schemes, identifying the correct order of three tactics and/or explaining the logic of its sequence.	Students can barely identify one of the existing ordering schemes, identifying the correct order of two tactics and/or explaining the logic of its sequence.	Students cannot identify any ordering scheme for lean tactics.
Students can apply lean tactics in the solution of lean problems	Students can completely solve specific lean problems applying the seven tactics, through the definition of their meaning and/or using examples as specific solution alternatives for the seven tactics.	Students can satisfactorily solve specific lean problems applying five tactics, through the definition of their meaning and/or using examples for these five tactics.	Students can partially solve specific lean problems applying three tactics, through the definition of their meaning and/or using examples for these three tactics.	Students can barely solve specific lean problems applying two tactics, trough the definition of their meaning and/or using examples for these two tactics.	Students cannot apply and explain lean tactics.

use outside sources to support their analysis of a case problem. In the Fall term, we used a shorter case and students completed the exam in class. For the in-class exam, students could use course materials but no additional references. The fact that students could produce similar results in the Fall in a shorter time frame might suggest greater familiarity with the material. Second, we have not yet completed the evaluation of our rubrics. For example, we will be examining consistency to ensure that different reviewers assign similar scores. Additionally, we may define additional dimensions or aspects to the objective.

Conclusions

This paper describes our implementation of lean laboratory exercises in an introductory production systems design course at WPI. The six laboratory exercises, based around a physical simulation of clock assembly called TIME WISE, encouraged students to experiment with theoretical concepts and critically examine process results. Students who took the course with the added laboratory exercises expressed significantly more confidence in their ability to understand and apply lean ideas, as well as to calculate process measures. Our preliminary scoring of student work showed little difference between those who took the course with the lab and those who did not. These initial results may be explained by differences in the format of the student work and/or the preliminary nature of the evaluation.

We are teaching the laboratory section of the course again in Spring 2003, and are continuing our evaluation of the project impact. In addition to lean design, project objectives include improving students' understanding of process dynamics and variability and their ability to make data-based decisions. We are testing rubrics to evaluate these objectives. Based on the preliminary results, we are also interested in examining student learning over a longer time span to see whether or not the context created by the laboratory helps students to remember what they have learned. We are also making several changes to the exercises, incorporating more required calculations and exploring supply chain impacts. Students who participated in the TIME WISE exercises in Fall 2002 were overwhelmingly positive about the laboratory activities in student evaluations. We also found the interaction and exploration required by the labs to be a stimulating and satisfying teaching experience.

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Biographical Information

Sharon A. Johnson is an Associate Professor and Director of the Industrial Engineering Program at WPI, where she teaches courses in facility layout, production planning, and process management. She received her M.S. and Ph.D. in Industrial Engineering from Cornell University. Her research interests include process analysis and modeling, case study development, capacity planning, and remanufacturing.

Arthur Gerstenfeld is Professor of Industrial Engineering and Management at WPI and teaches courses in production system design and managing technical innovation. He received his Masters and Ph.D. from MIT and has published more than fifty articles in academic journals and edited several books.

Amy Z. Zeng is an Assistant Professor and teaches in the areas of business logistics, operations management, and supply chain management at WPI. She received her M.S in Industrial Engineering from the University of Washington, and her Ph.D. in Operations Management from Pennsylvania State University. Professor Zeng has published numerous articles in the area of supply chain management.

Boris Ramos is a PhD student and a research assistant at WPI. He also teaches in the Electrical Engineering Department at ESPOL in Ecuador and has been Undersecretary of Telecommunications of Ecuador. He received his Masters in Computer Science from WPI and an MBA from ESPOL.

Saumitra Mishra is pursuing a Master's in Operations and Information Technology at WPI, with expected completion in May 2003. He received Bachelor and Masters degrees in Commerce from Gujurat Univeristy, and has worked as a software programmer.