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A Supply Chain Management Tool for Linking Courses in Manufacturing Engineering*

DANIEL WALDORF and SEMA ALPTEKIN
Industrial and Manufacturing Engineering, Cal Poly, San Luis Obispo, California, USA.
E-mail: salpteki@calpoly.edu

A recent Society of Manufacturing Engineers (SME) grant received by the Manufacturing Engineering Program at Cal Poly has provided funds to strengthen its curricular focus on supply chain management, flexibility, business skills, quality, and process controls. New courses and laboratories are developed in electronics manufacturing, information technology, and supply chain management. A functioning supply chain environment has been developed to provide vertical integration among several courses. A software tool being developed in-house integrates the activities of the students who play the roles of customers and suppliers. Details of the various components of this comprehensive project are presented in this paper.

INTRODUCTION

THE MANUFACTURING ENGINEERING PROGRAM at Cal Poly has earned a reputation for graduating highly-qualified, professional engineers, largely due to its learn-by-doing approach to engineering education. A Manufacturing Education Plan (MEP) grant has recently been received from SME to fund activities directed at closing some of the industry-identified 'competency gaps' presented in SME's Manufacturing Education Plan research [1] and communicated by our industrial partners.

The grant project hopes to encourage interest in the field of manufacturing engineering and increase the number of students pursuing a degree in Manufacturing Engineering. It will achieve this by upgrading equipment and lab facilities, strengthening coverage of the technologies and engineering trends in electronics manufacturing, and updating the Manufacturing Engineering Program curriculum. The curriculum changes reflect the changing landscape of US manufacturing, including renewed emphasis on flexible production and supply chain integration.

Based on the needs of local and regional manufacturers and in light of the growing dependence on information technology and supply chain management in all manufacturing industries, several new courses and laboratories are being developed. The new course content covers supply chain management, flexibility, business skills, quality, and process controls. Our freshman manufacturing lab sequence is being integrated so that students act as customers and suppliers for students in other courses. Furthermore, they will work in teams to increase overall production efficiency. Central to this ongoing project is the development of a supply chain environment to provide vertical integration among several courses. A software tool is being developed to facilitate the communication among students who play the roles of customers and suppliers as they take various courses in manufacturing engineering throughout the year [2].

OVERVIEW OF MANUFACTURING ENGINEERING PROGRAM

California Polytechnic State University, one of 23 campuses of the California State University system, is a largely undergraduate, teaching university specializing in applied technical and professional fields. With an almost century-long reputation for producing talented graduates through a hands-on, learn-by-doing approach, Cal Poly has also achieved wide recognition for comprehensive programs that include the arts, sciences and humanities. It is regularly included in 'best colleges' lists such as the annual ratings published by *US News and World Report*. For the eighth year in a row, *US News* ranked Cal Poly the top public regional university in the western United States.

The Manufacturing Engineering Program at Cal Poly, housed in the Industrial and Manufacturing Engineering (IME) Department, began in 1993 with the first class of seniors graduating in 1995. The program strives to educate students for distinguished careers in manufacturing engineering and related fields using the learn-by-doing approach that stresses integrated processes and appropriate

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technologies. Objectives include graduate readiness for manufacturing practice, engineering success based on a strong grounding in fundamentals, career success based on a well-rounded education, and the ability and desire for continuous learning.

Since Cal Poly students declare a major before entering, freshmen are immersed in their chosen fields often from the first day of instruction. Manufacturing Engineering students begin with 100-level lab courses that stress hands-on knowledge of specific manufacturing processes, including Net Shape, Joining, Material Removal, and Electronics Processes. Subsequent years are spent learning engineering fundamentals and gaining a deeper understanding of manufacturing design, processes, and systems. Most advanced courses have a lab component as well and require participation in product/process design projects involving problem-solving in teams. For example, in IME 241 Process Design I, students work together to design a detailed process plan and cost estimate for machining a small product (flycutter) using several operations. In IME 341 Tool Engineering, student teams design tooling solutions to produce a variety of self-defined products. In IME 418 Product-Process Design and in IME 455 Manufacturing Design and Implementation I, teams work with local industry to design real-world products, processes, and systems from concept to completion. In addition, every student at Cal Poly is required to complete an individual or small group senior project. Each student identifies, investigates, plans, and solves a real problem from industry or faculty research. The senior project is the logical capstone for our hands-on, laboratory-intensive undergraduate program and gives the student confidence and experience with project management. The senior project has proven an excellent segue to industry or graduate study for each of our students.

Currently, several courses are used to make up the freshman sequence of hands-on manufacturing experiences. These include IME 141 Net Shape Processing, 142 Joining Processes, 143 Material Removal Processes, 144 Introduction to Design and Manufacturing, 157 Electronics Manufacturing, and 251 Introduction to Manufacturing Engineering Analysis (the sequence typically spills over into sophomore year). Unfortunately, the labs and projects associated with these courses have not been integrated as they might be in a modern manufacturing organization—i.e., with interdependence of materials, schedules, and personnel. In coordination with curriculum re-design involving a newly-defined product that ties these areas together, the new SCM tool will be used to accomplish the integration of information by simulating a real manufacturing supply chain and illustrating the various facets of modern manufacturing systems. The course contents in several of these existing classes are being revised to incorporate new coverage of supply chains, flexibility, business skills, quality, and process controls.

ONGOING PROJECTS

Although a similar product had been utilized in the past as part of the freshman machining class, a new design for an 'air motor' (i.e., simple pneumatic-powered motor for driving a piston, crankshaft, and flywheel—see Fig. 1) will be used to tie the activities in the various classes together. In the previous version of the course, students machined the seven components they needed for the old motor assembly by individually staging through the required machining processes (turning, boring, drilling, broaching, milling), collecting finished components as they went, and finally ending the term by assembling them together to make their own completed motor. A similar sequence was followed in the net shape course and electronics course to complete separate products. The new motor design has cast components, machined components, and an electronic circuit board for sensing and displaying rotational velocity of the flywheel—all of which need to be joined and assembled together. In the new versions of these courses, students will no longer act as isolated producers of products in isolated silos of courses, but rather they will work as members of a supply chain to all produce components for the completed motor.

To date, several pieces of the larger supply chain picture have been realized. Pilot sections of IME 141 (casting) have been run during 2001–02 and 2002–03 to cast flywheels for the IME 144 (machining) class. The flywheel is a critical component in the air motor. Most of the flywheels for IME 144 had been purchased from an outside vendor who die casts them out of zinc. However, during the pilot sections groups of IME 141 students experimented with different methods for producing the flywheels. Each used a custom flywheel design that had been suggested by students in IME 144 from previous quarters. The

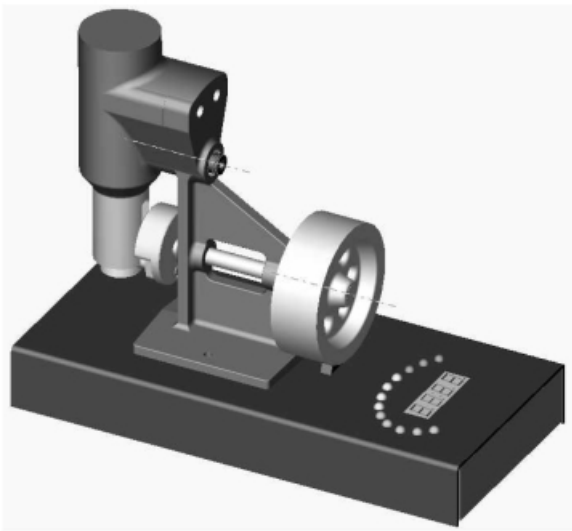


Fig. 1. Air motor.

groups all utilized 'rapid tooling' concepts in order to be flexible in their production. The three methods were:

1. Lost foam casting utilizing CNC cut layers of Styrofoam.
2. A crude rapid prototyping method of depositing hot wax in layers using a hot-glue gun connected to a CNC-controlled positioning slide. The hardened wax part (pattern) is then used in the Lost Wax method of casting.
3. A more sophisticated rapid prototyping method using the 3-D systems 3-D printer. This method uses state-of-the-art equipment to deposit layers of polymer to create a part from an STL file created from a CAD model. The created part (also a pattern) is then used for lost wax casting.

Various levels of success were achieved. Although most of the groups have been able to successfully produce cast flywheels, the quality and finish of the parts has been improving since the first sections. The 3-D systems rapid prototyping method and a new method (permanent mold cut by CNC) seem to hold the most promise for high quality parts and are being further developed and experimented within the current term. In addition, with a new furnace in place, additional materials are being considered for the flywheels (aluminum was primarily used with these groups and proved somewhat lightweight for a flywheel) to make them more functional and attractive.

Pilot sections have also been offered for the IME 144 (machining) class. Not only did the class have modest interaction with the IME 141 casting effort, but the main class project (the air motor) was run entirely as a team project rather than as an individual project, which had been the standard approach in the past. Four teams of five students are formed in each section to produce a total of twenty air motors. Although exposed in demonstrations to all the processes for the motor, each team was responsible for executing just two of the key operation steps on the product routing sheet. Each group produced ten identical components at these operations.

The results were dramatic. Each team experienced firsthand several key aspects of mass production that are not seen during individual part fabrication. The students learned:

- the learning curve in terms of mastering manual labor tasks;
- the importance of proper and efficient fixturing for holding more than one part;
- the need to plan for minimal part set-up, fixturing changes, and material handling;
- the concept of consistency in quality from one part to the next;
- the importance of a standardized process plan and operating instructions;
- the interdependence on other teams and suppliers in producing the final product;
- the role of individuals in a team effort aimed at maximizing productivity and quality;
- the effect of mass production on product costs.

None of these important concepts had been addressed in this class in the past, especially not in a hands-on way as experienced by these freshmen. The students also saw a tremendous increase in productivity and quality compared to the work done in previous course offerings (data and completed motors from past offerings were shared with the students and made readily available). In the past, students took more than four lab periods to complete the motors; while in this quarter all twenty were completed in two lab periods, with additional time to make quality measurements, cost estimates, and operation sheets. After measuring quality, it was found that the mass produced motors were much more consistent than those produced individually.

Pilot sections are now being offered for IME 157 and IME 251 (electronics manufacturing). Two students and one instructor have worked to design the new electronic tachometer for the air motor that will be produced in these classes. The component is actually a subassembly that includes a photoreflective sensor, a variety of LEDs, a printed circuit board including a programmed microcontroller chip, and a sheet metal housing to enclose the electronics and mount the motor. The product senses the rotational speed of the air motor, lights up a series of LED's proportional to the speed, and displays the RPM on a digital readout. The design has primarily been for a surface mount board to be produced on new automated assembly equipment donated by industry partners for our lab. The plan is for this subassembly to be produced in the electronics manufacturing class and delivered, as ordered, to the IME 144 class for final assembly. Working prototypes of the circuit, the board, and the housing have been completed, and students have now begun mass-producing the sub-assemblies in IME 251.

Several other curriculum changes have also occurred as part of the grant activities: new courses in Supply Chain Management and Information Systems Engineering were developed and offered; our existing process control classes IME 356 (Manufacturing Automation) and IME 416 (Process Control) have also been modified to introduce new technologies, especially related to computer network control; and our drafting and CAD sequence is being expanded to incorporate more computer-aided tools (including rapid prototyping) and CAM software modules. In all, the proposed curricular changes will not only reflect the new face of modern manufacturing industries but will also elicit a greater interest in manufacturing engineering from prospective students considering technical careers. We intend to attract students that would otherwise follow careers in computer science, computer engineering,

management information systems, or electrical engineering. Approximately 1000 students per year will be influenced by the changes as these courses are taken by students majoring in manufacturing, mechanical, industrial, aerospace, electrical, materials, and general engineering.

SUPPLY CHAIN ENVIRONMENT

The network of suppliers, factories, warehouses, distribution centers and retailers through which raw materials are acquired, transformed and delivered to the customer has come to be known as the supply chain [2]. Fierce competition in today's global markets has forced manufacturing enterprises to invest heavily in evaluating the supply chain. Items are produced at one or more factories, shipped to warehouses for intermediate storage, and then shipped to retailers. Consequently, to reduce cost and improve service levels, logistics strategies must account for the integration of the various levels in the supply chain. The integration of the supply chain requires coordination of the functions of production planning, purchasing, materials management, production, distribution, transportation, customer service and sales forecasting. Courses are being developed at various universities nationwide to better prepare the engineering and business students to manage complex supply chains [3].

Our first course in Supply Chain Management (IME 417) was developed in 1999 which has since then been offered as a technical elective [4]. Various textbooks [5, 6] and supplementary material have been utilized to introduce the state-of-the-art planning models and tools for design, control, operation and management of the supply chain. The course drew students from Industrial Engineering undergraduate and graduate programs. Student feedback has been very positive.

One of the highlights of the course was the use of a simulation game in classroom environment. There are several simulation games available to teach the concept [3]. The famous 'beer game' [7] was used when the course was first offered. 'Supplying Hoop Dreams' [8] was used the second year. Since 'Supplying Hoop Dreams' is built on a more complicated supply chain than the Beer Game, it is more suitable to simulate the supply chain environment that is being created at Cal Poly. The end product of 'Supplying Hoop Dreams' has several components that need to be assembled, similar to the air motor explained earlier in this paper. By playing this game, students were able to see the effects of their decisions on inventory levels, service levels, total cost, and lead times.

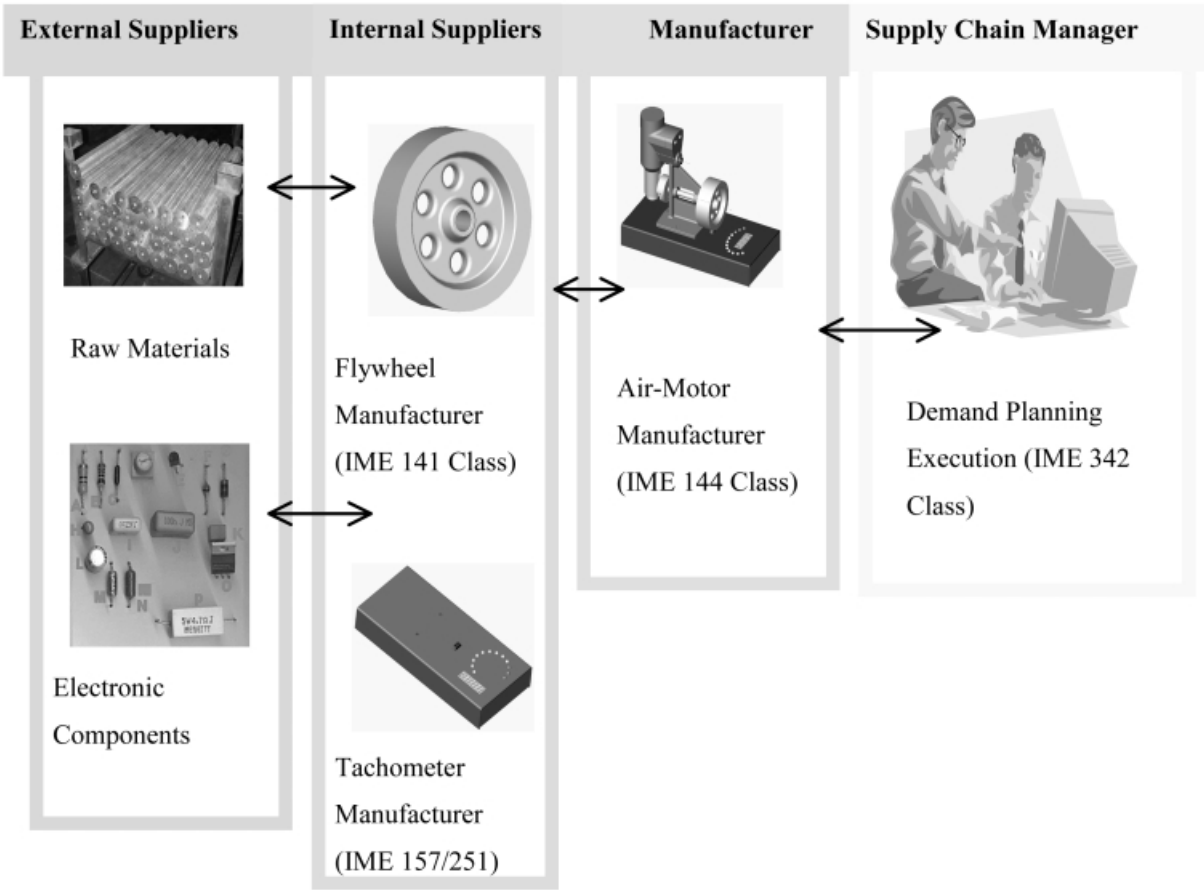


Fig. 2. Supply chain management environment.

SCM course module

Starting Spring 2002, sophomore level Manufacturing Engineering students were introduced to the major concepts of SCM in IME 342 (Manufacturing Systems Integration)—a required course for all Manufacturing Engineering students. The students implemented the SCM concepts in an environment that resembles an industrial setting. Figure 2 demonstrates this SCM environment.

A typical scenario in this SCM environment is as follows: the students in IME 342 develop production schedules to have the right quantity of products (air motor) delivered on time. Basic components of the air motors are then manufactured in the manufacturing engineering laboratories by Industrial, Manufacturing, Electrical, and Mechanical Engineering freshmen as they take the 100-level manufacturing courses offered by the IME Department. In the IME 141 course, students use CAD data to manufacture flywheels needed for the air motors. Students in each of the freshmen level courses will be introduced to SCM concepts as they use a collaboration tool to determine the order quantities and deadlines for the parts that they will manufacture that quarter.

The students in IME 342 are asked to manage the supply chain of the air motor. The integration of the air motor supply chain requires coordination of the functions of production planning, purchasing, materials management, production, distribution, transportation, customer service and sales forecasting. Some of these activities will be handled by the staff members (such as purchasing), but the overall supply chain integration activities will be carried out by students. They will make production plans for the Fall, Winter and Spring quarters of the following academic year. They will make decisions such as order size and manufacture in-house vs. outsource. They must take into consideration production capacity (e.g. class sizes of IME 141, 144), yield (e.g. number of students who drop the classes after the second week of quarter, hence affecting the number of components that could be manufactured by suppliers), inventory levels, lead time (e.g. the time it takes for students to manufacture air motor components in each supplier class), etc.

Development of the collaboration tool

A simple software tool can provide a collaborative environment for the students in the various manufacturing engineering classes as they simulate different players within the supply chain (see Fig. 2). A framework for this collaboration tool has been defined and designed, and interactive mockups of the final tool have been produced [9]. The main purpose of this tool is to enable visibility of supply chain data across the supply base. The intent is to share information among students in various classes so that better business decisions are made regarding inventory position, capacity constraints, lead time adherence, and forecast accuracy. This tool will facilitate communication among students who play the roles of customers, suppliers, and supply chain managers as they take various manufacturing engineering courses throughout the year.

In the process of developing the collaboration tool, we have worked with select alumni who have been involved with the development of SCM tools in industry. Among them were alumni working for Cisco. They had been involved with the development of a collaborative environment to share data between Cisco and its suppliers [10]. They acted as consultants throughout this project and provided services in the form of class presentations and conference calls as we made progress on our in-house developed tool.

The input of our consultants was most crucial when it came to making a decision on which software package to use. My SQL, MS Access, and MS Excel were considered as alternatives. The recommendation was to use MS Excel to develop the mockup during the early stages of the project.

Product A		
Sub-Assembly	**Part #**	**Qty**
Air Motor Frame	AMF	1
5 Spoke Flywheel	5SPFW	1
LED Tach, Stair Step	LED-SS	1
Tach Chassis, Stair Step	CHA-SS	1
Product B		
Sub-Assembly	**Part #**	**Qty**
Air Motor Frame	AMF	1
Round Hub Flywheel	RHFW	1
LED Tach, Stair Step	LED-SS	1
Tach Chassis, Stair Step	CHA-SS	1

Fig. 3. Sample bill of materials.

Once developed, it could then be overhauled to a database system (such as MS Access or My SQL) to benefit from general capabilities such as data mining and being able to map many-to-many relationships. Since many of our manufacturing engineering students are familiar with Excel, it was used in combination with the integrated Visual Basic feature for the initial phase of the software development project.

This tool is currently being developed as an intranet-based application that allows the students in various classes to order their parts through a graphical user interface linked to a common database. The students will enter the completion dates, scrap rates, lead times, and other operational data as they become available throughout the quarter. A bill of materials (BOM) for each product type is stored in the database (see sample BOM in Fig. 3). Performance measures will then be developed to check the original plans against the actual data obtained by students. Reports will be provided to the instructors who will act as supervisors to discuss accomplishments and take corrective actions, if needed.

Various screens of the mockup are provided in Figs 4 and 5. A very simplified version of the data flow is as follows. Demand for each type of air motor is entered into the system along with due dates by the students in the upper level course (IME 342) who simulate the supply chain manager (Fig. 4). Demand for each air motor is then broken down into demand for components using the bills of material (BOM) that are stored in the system for each motor type. Manufacture vs. purchase decisions are made, and order quantities for each component are passed along to the first-tier suppliers (IME144, 251/157) and to second-tier suppliers (electronic component suppliers, IME 141 students for fly wheel, etc.) Inventory positions and capacity constraints are also entered at this point.

Our plan is to make this tool available for our students on the Web to provide ease of access from different locations on campus since our laboratories are located all around the campus. We plan to have the customers (mainly our alumni) enter their orders through the Web. They will be given a chance to customize the design of the Air Motor by picking from a series of alternatives for the base and by picking different combination of LEDs for the tachometer chassis. We also plan to assign a serial number to each air motor as part of the shop floor monitoring system. With the amount of information to be stored, a database system will be justified.

Simulation game

Along with the development of the supply chain environment, a computer-based simulation game

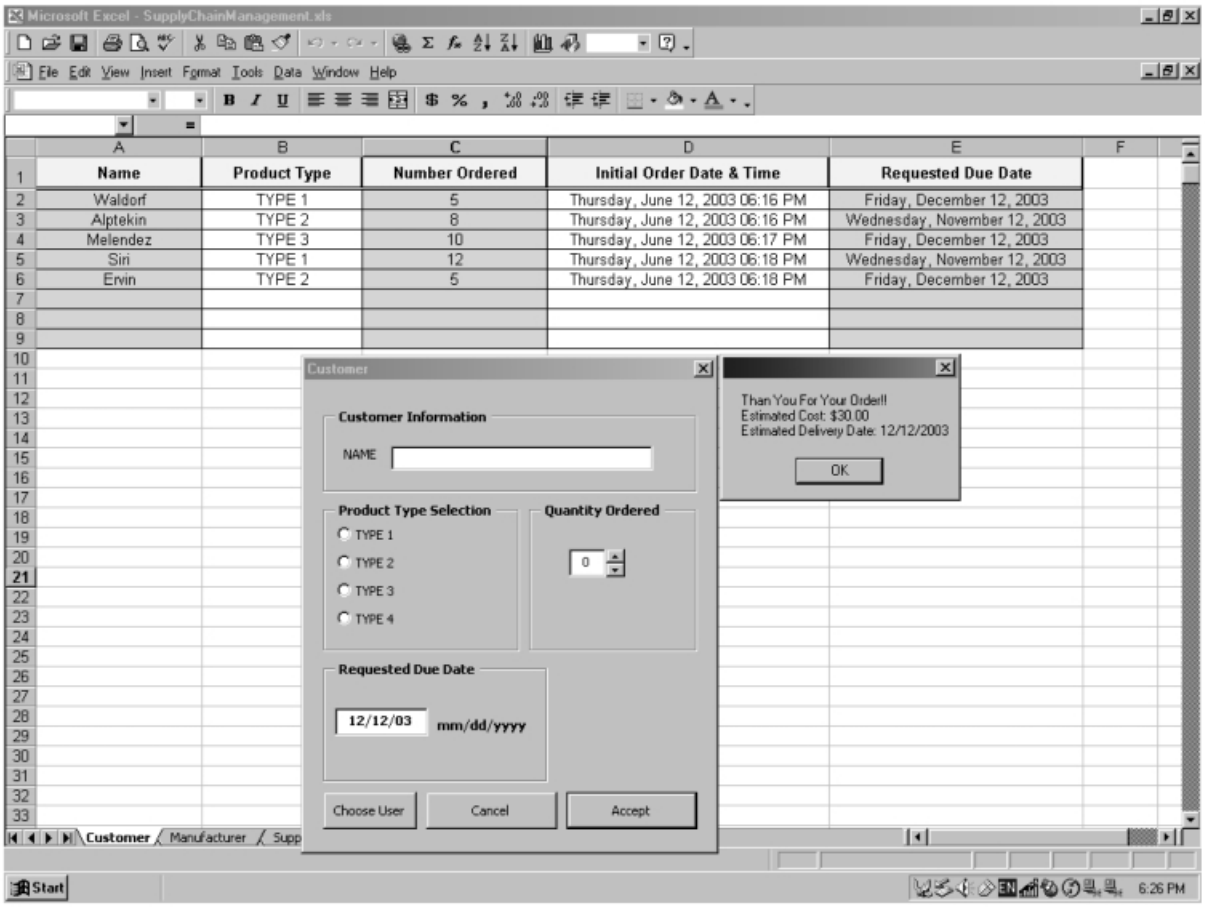
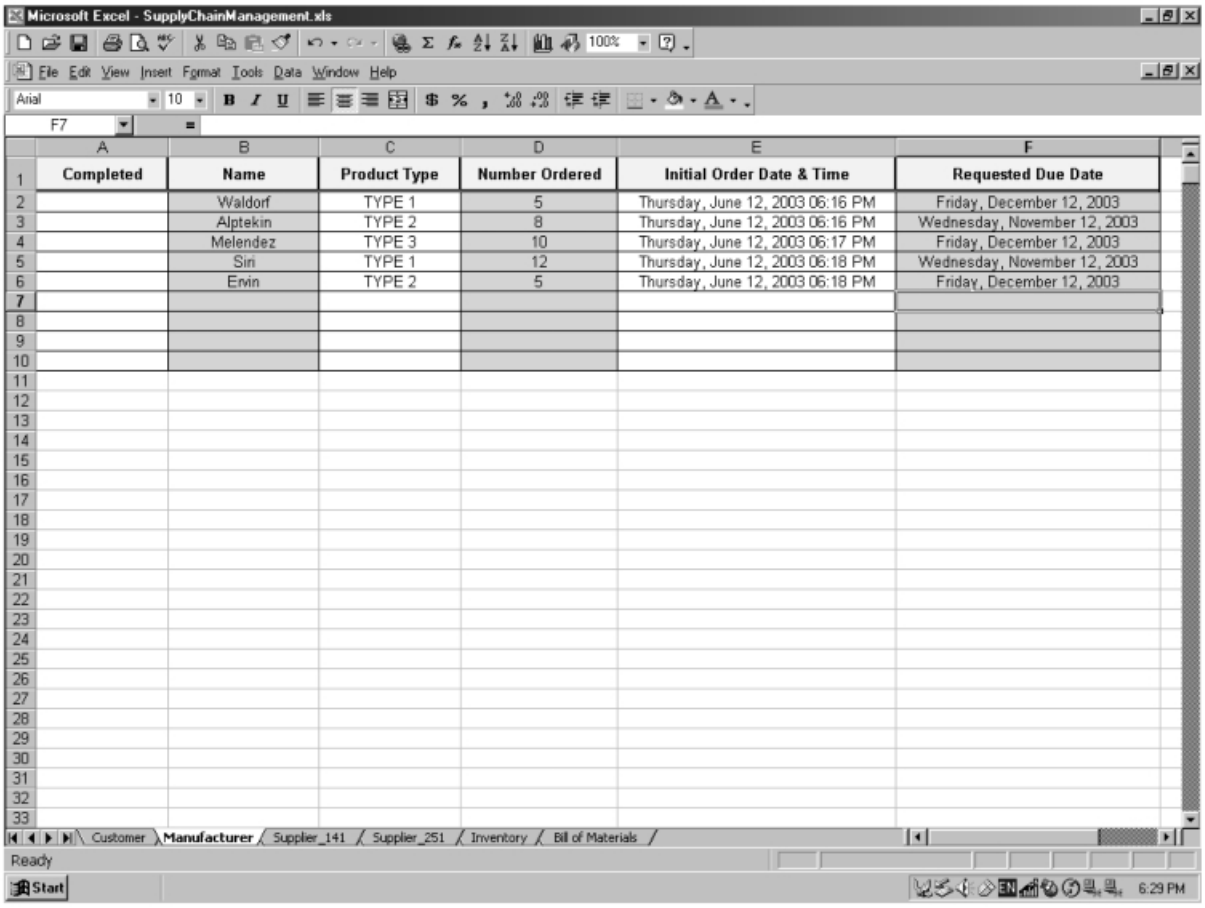


Fig. 4. Demand screenshot of the mockup.



Completed	Name	Product Type	Number Ordered	Initial Order Date & Time	Requested Due Date
	Waldorf	TYPE 1	5	Thursday, June 12, 2003 06:16 PM	Friday, December 12, 2003
	Alptekin	TYPE 2	8	Thursday, June 12, 2003 06:16 PM	Wednesday, November 12, 2003
	Melendez	TYPE 3	10	Thursday, June 12, 2003 06:17 PM	Friday, December 12, 2003
	Siri	TYPE 1	12	Thursday, June 12, 2003 06:18 PM	Wednesday, November 12, 2003
	Ervin	TYPE 2	5	Thursday, June 12, 2003 06:18 PM	Friday, December 12, 2003

Fig. 5. Manufacturing order screenshot of the mockup.

was developed to be used by the manufacturing engineering students. Many suppliers and retailers have observed that while customer demand does not vary much, inventory levels fluctuate considerably across the supply chain. This increase in variability in the supply chain is referred to as the 'bullwhip effect'. Human intervention in determining order amounts without accurate knowledge of the actual demand aggravates the situation with inventory levels, thus creating the bullwhip effect. This effect is obviously undesirable as it inflates supply chain costs (e.g. inventory holding, backlog, late delivery, under/over resource utilization, etc.). The source of such fluctuation and amplification of order amounts and inventory is mainly due to the lack of sharing of production information between entities in the supply chain [12]. Our in-house developed game is intended to show how the bullwhip effect is created and how it can be reduced with the use of centralized data. A simple supply chain system similar to the air motor supply chain is used as a model for this project. Microsoft Visual Basic 6.0 is the programming language used for the user interface and the simulation engine. A Microsoft Access 2000 database is used to store the simulation data. It also provides the framework to incorporate more complex scenarios of SCM to better represent the air motor supply chain of Cal Poly.

INDUSTRY INVOLVEMENT

Industrial partners have joined the Cal Poly manufacturing consortium and are committed to providing time, advice, and financial support for strengthening the Manufacturing Engineering Program by making it relevant and responsive to industry practices and innovations. Each industry partner has donated between $10,000 and $100,000 in cash, payable over two years (2001–2003), to finance labs, equipment, and a manufacturing engineering facility relocation as a match to the SME funds used for outreach and curriculum development. Over $300,000 in pledged support was received by the end of the first year by local and regional partners concerned with the continued success of the Manufacturing Engineering Program.

In addition to their financial support, consortium members have been involved with various activities including guiding and evaluating curriculum choices, sponsoring student co-ops and internships, giving guest lectures, and critiquing student projects. Consortium members meet twice a year to give specific guidance related to the facilities relocation (curriculum, equipment purchases, etc.). Already, advice from our partners in industry is shaping the future of the Manufacturing Engineering Program. The addition of new courses

in electronics manufacturing is a direct result of requests from companies such as Flextronics and Orthodyne Electronics that have experienced a shortage of fully-qualified, professional engineers trained in this area.

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CONCLUSION

A recent grant received from MEP of SME is providing us with the funds to strengthen our focus on several industry-identified 'competency gaps' presented in SME's Manufacturing Education Plan and communicated by our industrial partners. Based on the needs of local and regional manufacturers and in light of the growing dependence on information technology in all manufacturing industries, new courses and laboratories are developed in electronics manufacturing, information technology, and supply chain management. Central to this ongoing project is the development of course modules in supply chain management and a collaboration tool that integrates the activities of the students who play the roles of customers and suppliers.

The involvement of California manufacturing industry leaders has been crucial to the project's success, and their needs and advice have been particularly useful as the project progressed. Success of the project, as measured by student enrollment and retention data, as well as industry, alumni and student surveys, will impact several aspects of regional manufacturing: the Manufacturing Engineering Program will be able to graduate a greater number of better-educated engineers; students from across California will have an attractive option for studying manufacturing engineering and establishing successful careers in the field; and finally, regional employers will find talented, enthusiastic graduates who are better-equipped to meet today's industry challenges and contribute to company success.

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Daniel Waldorf is currently an Assistant Professor in the Industrial and Manufacturing Engineering Department at Cal Poly. He joined the faculty in 1998 after working in Chicago as a Quality Engineer for ATF, Inc., a supplier of cold-formed and machined components for the automotive industry. He received his Ph.D. in mechanical engineering in 1996 from the University of Illinois at Urbana-Champaign where he taught quality and applied statistics and researched machining models for monitoring and control. Dr. Waldorf serves as the Project Director for the SME MEP grant described in the paper.

Sema E. Alptekin is a professor and Department Chair at the Industrial and Manufacturing Engineering Department at Cal Poly, San Luis Obispo. Prior to joining Cal Poly in 1994, she was a faculty member at the University of Missouri-Rolla for ten years. There, she directed interdisciplinary research in Intelligent Manufacturing and taught graduate level courses. From 1990 to 1992, while on leave from UMR, she explored first-hand the problems faced by American manufacturing companies while working for the General Motors (GM) Corporation. Dr Alptekin has a BS and an MS in Mechanical Engineering, and a Ph.D. in Industrial Engineering from Istanbul Technical University in Turkey.