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Enhancing Undergraduate Engineering Education of Lean Methods using Simulation Learning Modules Within a Virtual Environment

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Abstract

This paper highlights the use of an integrated user-centered virtual learning environment through extensible simulation learning modules that is currently being developed to enhance undergraduate curricula to meet the industrial needs for engineers with education in lean. The purpose of the research is to address these expectations by developing learning modules that incorporate lean simulation models into various Engineering Management, Industrial Engineering, and Mechanical Engineering courses at Missouri S&T, Texas Tech, and South Dakota State, respectively. In recent years, increasing global competition, rapidly changing technology, and a deficit of U.S. engineering graduates have intensified the need to produce graduating engineers who are effective problem solvers and analytical thinkers, yet who can also collaborate on interdisciplinary teams to address complex, real-world systems. A key area of competence for many engineering undergraduate, as well as graduate, disciplines is the application of structured problem solving methods, e.g., lean, to improve the performance of organizational processes.

This virtual learning environment will enhance undergraduate engineering education by utilizing technology as a learning tool in lean, by fostering student development through active learning in the classroom, and through projects based on current real-world challenges, thus improving student learning, motivation, and retention. The paper highlights the learning modules to be developed in the virtual learning environment. The long-term goal is to evaluate the impact of the curriculum changes on student learning, outreach, and industrial collaboration.

Introduction

The National Academy of Engineering (NAE) has identified that the Engineers of 2020 need to have strong analytical and problem solving skills while being readily adaptable to rapidly advancing technologies in an increasingly globally interconnected world (1). The NAE recommended that engineering educators develop an undergraduate curriculum that provides students with learning opportunities utilizing the latest technology within interdisciplinary teams in addressing real and meaningful challenges (2). This is not the way in which lean methods are currently taught. A typical lean curriculum currently consists of some instructional lectures, a course project done at some company (if possible), one or two case studies and perhaps some manual simulations through seminars. The most important aspect to note here is the lack of usage of virtual engineering simulation modules, resulting in a limited scope for experimentation even though lean methods require the analysis of a working process, as well as the opportunity to test solutions in practice. Due to this limitation, students have a limited access to knowledge of real life barriers in lean implementation.

While existing instructional techniques are undoubtedly valuable and should be maintained as part of the curricula, the introduction of simulated learning exercises in a virtual environment would greatly increase the effectiveness of current curricula by providing greater access, standardization, and control than course projects, and greater depth and realism than manual simulations. In this paper, we have discussed a proposed way to transform the traditional curriculum of lean and related courses to a curriculum which would enable better understanding through practical work in virtual engineering simulation modules and would be suitable for distance education (many times students for lean courses are company executives, thus distance learners). Therefore, the research described in this paper aims to improve the educational experience for Industrial Engineering (IE), Engineering Management (EMGT), and Mechanical Engineering (ME) graduates, including motivation, retention, and ability to apply lean principles to real world settings, by enhancing courses and curricula through simulation modules and a virtual learning environment, allowing active learning in the classroom and team projects based on current real world issues. In this paper, we focus on the creation of virtual engineering learning modules for lean and related courses. The implementation of these modules is scheduled for the fall semester of 2011.

Motivation and Review of Related Work

The American Society for Engineering Education (ASEE) reported statistics for the 2005-2006 academic year indicating that engineering graduation and enrollment rates at U.S. universities were not in line with the country's increasing demand (3). The deficit in engineering students does not appear to be due to an inherent lack of interest in the field, but to a lack of exposure to the hands-on aspects of engineering jobs. Recent research suggests that many high school students express interest in STEM disciplines but are not pursuing them due to lack of knowledge of exactly what is involved in the day-to-day reality of the jobs(4, 5). Meanwhile, hands-on instructional techniques have been shown to be effective in increasing student interest and understanding of STEM disciplines, starting in K-12 levels (6, 7, 8, 9). In fact, an Advisory Committee report, under the auspices of the Education of Human Resources (EHR) Directorate of the NSF, stated that:

> "Insofar as every science depends on data for both theory and application; laboratory or field data collection experience is an absolute necessity. Adding up numbers from a textbook example is not the same as recording those numbers or qualitative observations based on one's effort. When students "own" their data, the experience becomes a personal event, rather than a contrived exercise."(10)

Even though this statement is fourteen years old, it still remains true today. Many U.S. engineering schools are accordingly attempting to change their curricula and teaching methods from an emphasis on theory to an emphasis on problem-solving and interdisciplinary teamwork. Purdue University, for example, is addressing this challenge through increased emphasis on hands-on learning throughout its engineering curricula, taking first year students "out of a massive lecture hall" and immersing them in hands-on design processes through work in a new Ideas to Innovations Learning Laboratory, which includes a Design Studio, Innovation Studio, Rapid-Prototyping Studio, Fabrication and Artisan Laboratories, and Demonstration Studio (11). Given that children under 18 spend on average over an hour a day using computers (12, 13), one of the hands-on instruction methods with the most potential to inspire and enhance the educational experience of the 'web generation' (14), is the use of computer simulations and virtual environments (15, 16).

In 2006, the National Science Foundation published a report focused on Simulation Based Engineering Science (SBES) (17). Simulation is defined as the application of computational models to the study and prediction of physical events in the behavior of engineered systems. SBES is defined as the discipline that provides the scientific and mathematical basis for the simulation of engineered systems, and fuses the knowledge and techniques of traditional engineering fields—industrial, mechanical, civil, chemical, aerospace, nuclear, biomedical, and materials science—with the knowledge and techniques of fields such as computer science, mathematics, and the physical and social sciences.

The specific benefits of using computers for promoting active learning have been recognized for several decades (18). For instance, Squire (16) documents the history of one type of virtual environment, video games, in the American culture and their introduction into education. Video games were first used for drills and practice games for factual recall, and have evolved into simulation and strategy games in order to model a system that is more consistent with the complexity of reality. Squire argues that video games enable learners to interact directly with a complex system, which helps the learner understand the system's dynamics. Evaluating the effectiveness of these virtual simulations has been the focus of other studies. For example, Freitas and Oliver (15) evaluated the effectiveness of educational games and simulation with respect to their particular learning context and subject area. Their research presents a four-dimensional framework to evaluate the potential of using games- and simulation-based learning. The framework dimensions include context (classroom-based, outdoors, access to equipment, technical support), learner specific (learner profile, pathways, learning background, group profile), mode of representation (level of fidelity, interactivity, immersion), and pedagogic considerations (learning models used, approaches taken). The format of the framework helps educators evaluate potential games and simulations.

Current case studies of applications also suggest that the use of computer simulation and virtual environment can enhance learning and education in diverse subject areas within engineering curriculum, as well as other educational settings, including the U.S. Army and medical schools, and K-12 education. For example, North Carolina State University recently partnered with the video game producer, Virtual Heroes, to develop video game simulations intended to promote high school student science and technology skills and interest in STEM disciplines (19). In addition, defense contractors Northrop Grumman Corp. and Lockheed Martin Corp. recently committed to an innovative partnership to develop high-tech simulations to enhance STEM education in the Baltimore County schools Maryland (20). However, despite the growing recognition of the potential of virtual environments to promote STEM education, as of recent count, less than one percent of schools taught through virtual environments (21). Thus, there is significant scope for expanding the use of this valuable instruction mode to applicable engineering contexts, including lean. In fact, lean is particularly well suited to these methods as it is both technically relevant and can provide results that are readily visualized for the user.

Overview of Lean Methods in Education

Enterprise Engineering has been defined as the body of knowledge, principles, and practices having to do with the analysis, design, implementation and operation of an enterprise (22). In a constantly changing competitive environment, enterprise engineering addresses a fundamental question: "How to design and improve all elements associated with the total enterprise through the use of engineering analysis methods and tools to more effectively achieve the organization's goals and objectives." As increased global competition drives firms to operate more effectively and intelligently, today's enterprise must expand its boundaries to include all components of the supply chain in order to efficiently make decisions and effectively handle disruptions. These complex and multidisciplinary systems have given rise to a need for improved engineering curricula based on integrative real-world scenarios, including team-based, open-ended projects. In fact, accreditation requirements have called for a response to changing education needs (23, 24). Many engineering programs have responded by developing new capstone courses in order to provide students with the ability to adapt to ever changing environments (25,26,27,28,29), as well as increased instruction in structured problem-solving techniques. Nevertheless, integrative curricula that meet the needs of modern education by using interactive collaborative learning environments are still lacking.

A key factor of Enterprise Engineering practice and education is lean, which has its origins in the teaching and writings of Total Quality Management (TQM) and Just-In-Time (JIT). Lean espouses the idea of "delighting the customer through a continuous stream of value adding activities" (30). Specifically, it is an extension of the idea of "world class" as defined by Schonberger (31): "… adhering to the highest standards of business performance as measured by the customer." Lean as a philosophy, therefore, is not about just doing better than competitors (32); it is about going beyond and being the best in every process and product.

The origin and general evolution of the lean philosophy and some of the basic techniques first brought into use by the Toyota Corporation are discussed by Papadopoulou and Özbayrak(33). The so-called Toyota Production System (TPS), which includes the JIT philosophy and other associated tools, is the original lean implementation. A main challenge to undergraduate engineering schools is how to equip graduating engineers with the tools, resources, skills, and experience needed to succeed in applying lean techniques in real-world settings.

Part of the challenge is due to the fact that applying lean tools requires tailoring to different production contexts (34) and also affects the social as well as technical systems of the organization. For example, one organization, Textron Defense Systems (TDS) abolished functional groups and restructured around core processes to support lean implementation (35). Similarly, Warner Robbins Air Logistics Center (WRALC) understood the importance of changes in many of its internal systems, such as the technical system, the behavioral system, and the management system, to support lean implementation (36). Other organizations have also found it necessary to restructure social as well as technical systems, including leadership and support infrastructure systems, such as Information Technology/Information Systems (IT/IS)(37). In addition, lean implementation requires the recognition of linkages to external parties, i.e., the extended supply chain. For instance, in their lean implementation, Lockheed Martin Aeronautics Company (LMAC) applied a system-of-systems approach, recognizing their interactions with both upstream influences and downstream customers (38). External factors may seem internal when the external agents are treated as parts of a larger enterprise. Then, many of the organization's customer-supplier relationships would be within the scope of lean enterprise efforts (39). An effort in this direction is the development of pull systems with suppliers (40). In order to build stronger linkage with key suppliers, a team from Rockwell Collins trained a team from the supplier company through classroom and lean events (39). Boeing introduced the Continuous Cost Improvement Program for suppliers, wherein suppliers needed to promise regular price decreases for continuing or obtaining business contracts. It also offered advice and its own experience in helping suppliers to aggressively apply lean (39). Thus, lean implementation must be approached and taught with both a context-specific viewpoint and a systems viewpoint that covers the extended supply chain.

In addition, there is a need for students who are learning about lean implementation to also be able to apply different quantitative tools to evaluate the effects of lean implementation. For instance, Worley et al., (41) compared the kaizen events within an organization using a mixture of objective and perceptual measures. This study found that, even within an organization with successful events and established processes, opportunities existed for improvement. Statistically significant differences between events were observed on a number of perceptual measures. This suggests that lean transformation is a continuous process which can benefit from analysis within a statistical framework (42). Statistical analysis tools can be combined with computer simulation methods to scientifically analyze the impacts of a variety of applicable lean methodologies.

Computer simulations have been used to understand the impact of lean in field settings, although they do not appear to have been deployed in educational settings. For instance, Abdulmalek and Rajgopal (34) analyzed lean benefits for a process sector application in a large integrated steel mill by developing a simulation model to contrast the before and after scenarios of lean implementation. The simulation output included basic performance measures used to analyze various system configurations for process improvement decision-making. Simulation modeling was also applied in the research of McDonald et al. (43), which focused on assigning workers to tasks in a lean manufacturing cell in an electronics assembly plant. The model addressed production requirements to meet customer demand, skill depth requirements for tasks, varying quality levels based on skill depth, and job rotation to retain skills for a cross-trained workforce, while minimizing net present cost. The model output provided worker assignment schedules for cross-trained workers under several alternatives. The alternatives were evaluated using costs from an optimization model and simulation model. Finally, Detty and Yingling (44) used simulation to support decision making for implementing lean manufacturing principles in an assembly operation. A model was developed for an existing system, which included the manufacturing processes; associated warehousing, inventory management, transportation, and production control/scheduling systems. The model was used as a tool to quantify the impact of implementing lean manufacturing techniques during the planning and evaluation stage. The model generated resource requirements and performance statistics for the current and proposed systems. These example applications indicate that computer simulation can be effective in promoting systems understanding of the impacts of lean implementation. However, as computer simulation of lean environments has not yet been expanded to educational settings, there is significant scope for work in this area. The proposed simulation modules and virtual environment to be designed and implemented in this research support the development of students' abilities to manage lean as a system, including recognition of the relationships between technical and social system factors and internal and external systems.

Model Development

The first step for implementing a virtual simulation platform for lean manufacturing education is to create a layout of the facility within a virtual environment. The virtual environment allows one to change machine configurations and performance metrics according to the topics being covered in a module. In the current project, this was done using VE-Suite, an open-source virtual engineering software package (45). This software was selected for its ability to merge visualization of 3D graphical models and numerical solvers. Specifically, VE-Suite uses three modeling engines: VE-Xplorer for visualization of the facility layout and processes, VE-CE to allow for the creation and operation of computational models, and VE-Conductor to allow for user interactions [Fig. 1]. 3D graphical models of the machines used in this simulation were modeled using Blender (46).

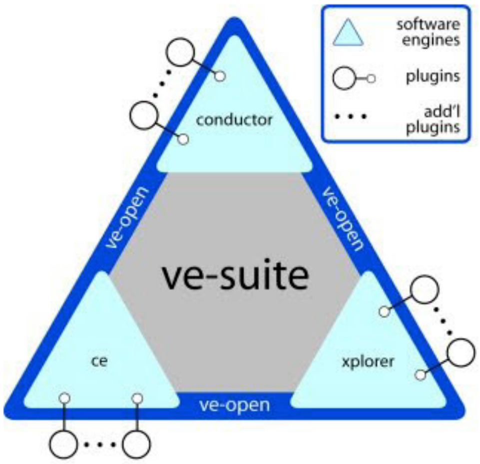
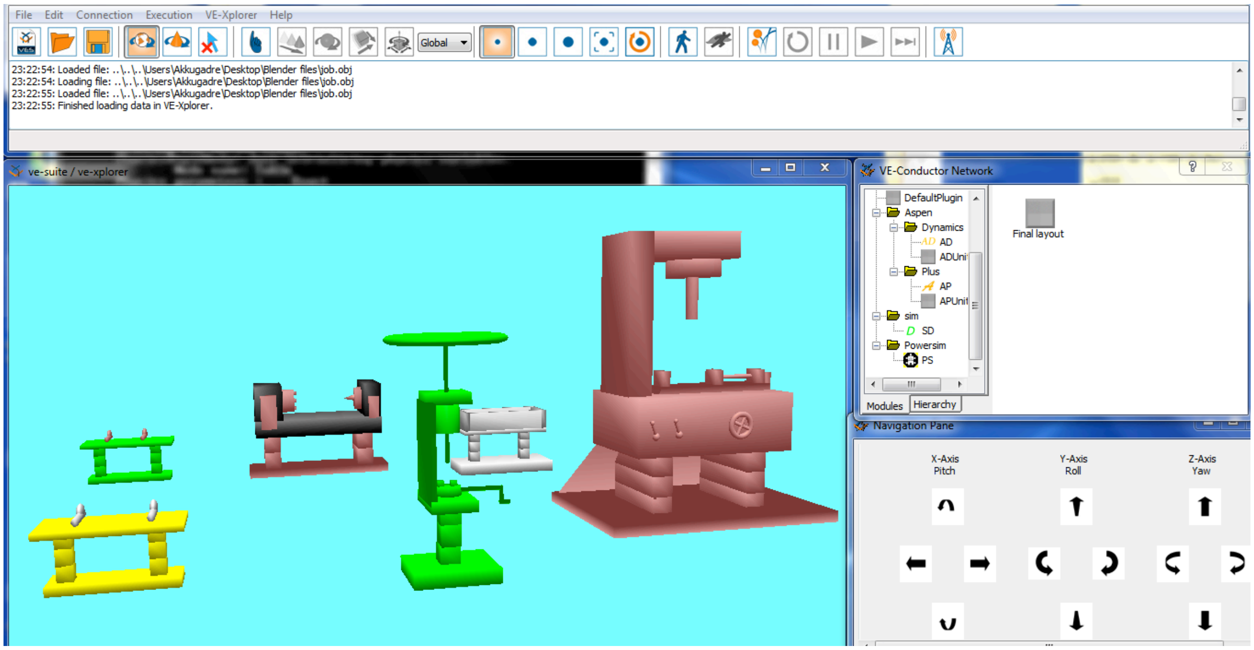


Figure 1 VE-Suite Architecture



```
23:22:54: Loaded file: ..\..\..\Users\Akkugadre\Desktop\Blender files\job.obj
23:22:54: Loading file: ..\..\..\Users\Akkugadre\Desktop\Blender files\job.obj
23:22:55: Loaded file: ..\..\..\Users\Akkugadre\Desktop\Blender files\job.obj
23:22:55: Finished loading data in VE-Xplorer.
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Figure 2 Layout of the facility in VE Suite

The CAD files created to represent the machinery for this simulation were then converted to a format compatible with VE-Suite. These graphical models were imported into VE-Xplorer, the graphical engine of VE-Suite. A layout was then arranged to simulate a manufacturing line [Fig. 2], and the models used to represent the stations were then assigned properties to reflect their physical appearance. The next step was to write the programming code for the mathematical models used to simulate the production line, such as Little's Law. C++ language was used to create these models to allow for the creation of a computational unit for use in VE-Suite. A graphical user interface was then designed to allow the students to provide input to the simulation. This was written using an open source software tool (WX widgets). To aid in the construction of this interface, Anthemion Dialog Blocks 4.39(47) was used [Fig. 3], and the resulting interface was used in VE-Suite's VE-Conductor engine.

Figure 3 User interface for Little's Law

The final step was to integrate the model, the code, and the user interface using the VE-Open framework. This makes it possible for the user to enter the production data such as work in process (WIP) and throughput to obtain output such as cycle time (CT) and other production parameters. Ultimately as the user enters different values of the data the solution will be shown in the gauges which will give the exact effect of change to the user. Details on the use of VE-Suite can be found online at www.vesuite.org(46).

Model Concepts

This section of the paper shows how the various concepts of lean can be applied to a virtual process. The single basic idea underlying the lean philosophy is to identify wastes or non-value adding (NVA) activities and continuously work towards eliminating or at least reducing them. Lean identifies seven major types of wastes that can be present in a system (48) including:

(1) Overproduction: producing more than required or earlier than required.
(2) Transportation: all the movement of the products or WIP to and from storage. WIP refers to all the unfinished goods in the production process which are waiting in queue before a machine or being stored in the warehouse from where they can be later retrieved for further processing.
(3) Motion: movements performed by operators and machines before, during, or after the process.
(4) Waiting: holding time for WIP or waiting in queue in front of machines as well as idle times for operators and machines.
(5) Over processing: NVA processing and use of materials, tools, and equipment.
(6) Inventory: accumulation of raw materials, WIP, and finished goods.
(7) Defects: reworked and scrapped products.

One of the most important wastes of production is inventory. The higher the level of WIP during production, the higher the inventory cost and potential for hidden quality problems in the final product. Thus, the focus of lean is to keep WIP to a minimum. Little's Law states that, under steady state conditions, the average number of items in a queuing system (WIP) equals the average rate at which items arrive (throughput or TH) multiplied by the average time that an item spends in the system (cycle time or CT), as shown in Equation 1 (49).

$$\text{WIP} = \text{TH} * \text{CT} \qquad (1)$$

Therefore, to find the WIP it is necessary know the cycle time and throughput at the given time. Further, to solve for cycle time, the equation can be transposed. To reduce the cycle time it is necessary to reduce the WIP and/or the throughput. Various lean concepts impact WIP differently. While the current model is simplistic in factors, there are several tools which will be applied to impact the overall cycle time of the process. The following provides brief descriptions of several commonly used lean concepts.

> *Single Minute Exchange of Dies (SMED)* refers to a quick changeover of equipment from manufacturing one part to the next part (48). This is essential when thinking in the terms of single piece flow and flexibility. A user, when designing a quick changeover, can make the model in the virtual simulation and also can modify the changeover time. Thus, if a user implements SMED they reduce the process time, the effect of which is seen as reduction of cycle time.
>
> *Single piece flow* is the ideal state in which no inventory is waiting to be processed and one product is being worked upon at every station (48). The goal is to bring a process as close as possible to this state. The number of pieces in the flow will affect the waiting time and ultimately the cycle time.
>
> *5S and cells* are principles to arrange a layout and differentiate between the required and not required material(48). Users can move the models around in the virtual environment and achieve the desired layout. This will allow the users flexibility in the number of operators and cycle time which can then be compared to takt time. Takt time is the frequency with which the customer wants a product or how frequently a sold unit must be produced. The number is derived by dividing the available production time in a shift by the customer demand for the shift.
>
> The *bottleneck* is the station that severely impedes the capacity of the whole system and that is unable to respond to sudden changes in demand (50). Users can find the bottlenecks based on machine cycle times and improve the process virtually by modifying the number of machines or the layout (line balancing). This will reduce the WIP and ultimately the cycle time.
>
> *Kaizen* is the principle is at the heart of lean as it indicates the need for constant improvement (48). Users can indicate necessary improvements with a starburst and accordingly work to make the changes. For instance, these improvements might focus on reducing the process time or the waiting time at each station, thus reducing the WIP and ultimately the cycle time.

Conclusions and Future Work

The virtual simulation tool can be used as a virtual laboratory for lean related courses. Students will be able to perform experiments and immediately see the effects of suggested changes in the production line. The students will also be able to calculate the time and money saved by process improvement changes. Thus, this module will help students learn through hands-on experimentation, improving learning retention and also enabling them to discover mistakes which could be costly if made in reality.

Future work involves completing the development and initial testing of the learning modules described in this paper, and then deploying them in targeted courses for full testing and evaluation of their effectiveness in enhancing student learning. In addition, other areas for future work include developing a simulated supply chain by substituting universities as vendors making the module more realistic (a combination of vendors, main company, and the customers) and thus setting up a complete manufacturing process. This would give the users even more insight into lean and supply chain management. Furthermore, the module can be used by companies for analysis before implementing any changes in their processes.

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