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Engineering Graphics Education for the Digital Enterprise: A Practical Example in a Large Freshman Engineering Course

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Abstract

With the advent of Industry 4.0 and digital enterprise environments, the importance of Product Data Management (PDM) and Product Lifecycle Management (PLM) continues to grow in industry, yet it is the exception rather than the rule in engineering and technology education. In this paper, we discuss an approach to CAD instruction where students work and develop their skills in the context of a digital enterprise environment. Our goal is to expose engineering students to the concepts, capabilities, and processes involved in the digital enterprise so they can become familiar with the tools and methods they will encounter in their future careers. We discuss the resources and tools that were specifically developed for this course, as well as the technology, workflows, and digital environment that were implemented to replicate a modern industrial ecosystem. We also discuss the challenges faced during the implementation, and some strategies to overcome these obstacles. This course redesign is the first step toward a significant curricular revision in our major and the deployment of PDM as a common infrastructure for all courses. Our approach represents a shift toward driving industry practices and processes into the engineering classroom, and provides a framework to fill the gap between theory and practice.

Introduction

Industry 4.0 is transforming the manufacturing world. Engineering firms are investing heavily in digital transformation initiatives and paradigms such as the Model-Based Enterprise (MBE) are rapidly becoming the new standards for doing business [1]. Engineering and technology education, however, has arguably been slow to respond to this new reality, particularly from a data and information management standpoint. Although engineering curricula have evolved to incorporate emerging technologies such as artificial intelligence (AI) and machine learning, concepts like Product Lifecycle Management (PLM), enterprise systems and tools, and business processes and workflows are typically ignored, and expected to be learned on the job or through internships [2]. Many companies find themselves caught between an incumbent engineering workforce that is slow to adopt new technologies and an incoming generation of engineers that lack the fundamental skills required to operate in an enterprise environment. Computer-Aided Design (CAD) is a notable example, as this discipline is often taught without a proper context.

Traditionally, 3D CAD courses have focused almost exclusively on the creation of parts, assemblies, and drawings using a particular software package (usually a parametric solid modeler). This practice is also widespread in most corporate training courses used by large engineering and manufacturing organizations to train newly on-boarded engineers. The CAD system is taught independently from the enterprise environment and the company's documented processes. As a result, institutional knowledge and coaching from seasoned engineers within the organization is required to supplement the tool training.

For more than thirty years, this Midwestern University has required all Freshman engineering students to take a Graphical Communication and Spatial Analysis course that addresses the connection between engineering design data and graphic communication. The course content has always revolved around mastering a specific CAD tool. Beginning in the Fall semester of 2021, however, the course was redesigned to emphasize the process, not simply the tool, and teach CAD in the context of the larger digital enterprise infrastructure. To this end, the improved version of the course emphasizes design intent [3] and the use of efficient parametric modeling strategies to facilitate design changes [4, 5]. Practical examples are demonstrated in Siemens NX, an enterprise-level CAD software, but the focus is more on strategic knowledge, i.e., the general process and techniques that can be applied to any CAD package, and less on procedural knowledge, i.e., the features, commands, and functionality of NX [6]. The goal is to facilitate the transfer of knowledge gained in the course to other CAD systems, thus lowering the learning curve of other software tools students may encounter in the future. In addition, an enterprise PDM system was deployed to manage assignment data and the course as a whole. The goal was to assert the importance of PDM and PLM, while providing practical exposure to the mechanisms used in a digital enterprise for storing, sharing, and managing digital product data, as well as communicating with others.

In this paper, we describe the organization and administration of the course, the deployment and configuration of technology, the general course management strategies, and the experiences of the students as well as the instructional team. Our results and lessons learned provide insights for the evolution of engineering and technology education, particularly the role of CAD in the development of digital enterprise curricula.

Background

Modern engineering and technology education is tightly coupled with the concept of "Industry 4.0," which focuses on the digitization of the manufacturing ecosystem [7]. Universities are devoting large amounts of resources to develop curricula, programs, and facilities to align with industry practices, standards, and tools, while active, experiential, and project-based learning approaches provide the theorical frameworks to foster environments of intrinsic knowledge development [8, 9]. Kolb's learning model [10], for example, defines a cyclic four-stage model (concrete experience or "feeling", reflective observation or "watching", abstract conceptualization or "thinking", and active experimentation or "doing") which considers "learning" as a continuum, rather than discrete pockets of time, and generates intrinsic motivation in learners. Similarly, authors Poitras & Poitras [11] stated the importance of apprentice style education for engineering, an approach that leverages active participation, hands-on exercises, and active experimentation, and use technology to enhance learning outcomes and facilitate the understanding of industry workflows and the terminology used by professionals [11].

According to Götting et al. [12], the alignment of engineering and technology curricula with Industry 4.0 goals must consider product development as flexible and interoperable. The singular viewpoint of highly specialized knowledge is replaced with a broader viewpoint that explains the context and interdependencies of the technology, which requires the re-evaluation of learning objectives and educational course content [13]. The authors also highlight the importance of interdisciplinary team projects and the incorporation of industrial technology in the labs.

The role of technology is key when implementing curricula that enables the Industry 4.0 paradigm. In particular, our study discusses the deployment of a PLM system in an engineering graphics course as a mechanism to expose students to relevant business processes, digital thread, and data management practices that are commonly used in industry. According to Pezeshki et al.

[14], “a PLM method can be viewed as a sophisticated tool for analysis and visualization, enabling students to improve their problem-solving and design skills, but more importantly to improve their understanding of the behavior of engineering systems.”

The importance of PLM in engineering education was discussed by Fielding et al. [15] and some instructors have reported successful implementations of Product Data Management (PDM) systems to support collaboration within large teams in multi-CAD environments [16, 17]. In this paper, we build on our previous work [2] to provide a complete software infrastructure to support CAD instruction in a large freshmen engineering course and to automate common processes, interaction, and communication among students and the instructional staff.

Course Information and Process Redesign

“Graphical Communication and Spatial Analysis” is a first-year engineering course taught at Purdue University and offered every semester (Fall, Spring, and Summer). Student enrollment is approximately 650 students per semester and the course is structured as a 2-credit lecture/lab. Weekly lectures take place in a large traditional classroom environment and labs are broken down into 30+ sections of approximately twenty students per section. Students are required to submit three to four assignments weekly throughout the semester.

The original version of course has historically been stigmatized by engineering students, who consider it “just a CAD class.” Because of this perception, many students underestimate the workload of the new format and pay little to no attention to the methodologies and processes involved, not realizing the importance that CAD plays in the new Industry 4.0 Model Based Enterprise (MBE). To combat these perceptions and provide a more relevant and realistic learning experience, the course was systematically transformed to emphasize design for change and product data management, which shifts the focus from merely creating geometry in a CAD system to building reusable models in a collaborative digital enterprise environment.

The course is designed to provide a strong foundation in engineering graphics, particularly parametric solid modeling, design for change, and the processes, data flows, and technologies involved in a digital enterprise through the lens of Product Data Management (PDM). These components were combined in a synergistic manner so that all CAD work occurs through PDM, which serves as a supporting course management system. In this course, all documentation, assignments, and lab materials are made available via a Learning Management System (LMS) and the submissions are stored and tracked using a PDM system. The students are asked to submit their CAD work to the PDM system, applying industry concepts such as Creating a Product Structure and signing off the submission via an Engineering Change Order (ECO). The introduction of such processes is embedded into traditional teaching concepts, such as assignment rework and regrading. Grading and feedback are initially provided via the PDM system, and later reflected in the Learning Management System to ensure a cyclic information flow process is achieved.

A midterm and final lab practical were implemented as additional assessment mechanisms. They are modeled after an industry CAD system competency certification, where students are given a fully dimensioned drawing of a mechanical part and a set of parameters and are then asked to create the 3D model of the part within a predefined time limit. Throughout the practical, students must apply a series of geometric changes to the model and report the mass of the part. Design intent is specified within the drawing and is later validated and scored by the instructional team to ensure the model reacts properly to the requested changes and behaves in a predictable manner.

Most students enrolled in the course have previous CAD experience, either through courses they took in high school or their own interest. The availability and affordability of software tools such as Autodesk Fusion 360, TinkerCAD, or OnShape, to name a few, have done a lot to introduce students to the world of 3D modeling. However, it also presents a challenge for foundational courses that strive to prepare students to design in the context of a larger system and instill efficient modeling habits. To combat these preconceived ideas of what CAD is and how it is used, students are informed in the first lecture that the course will mimic a medium-sized engineering company where the instructor serves as the engineering design lead, the teaching assistants take on the role of first line supervisors, and the students serve as engineering contractors. As a contractor, the students are provided with Assignment Requirement Documents that they must complete to standard to receive maximum points which serve as the currency for the course. This scenario puts the student in the frame of mind that they are not simply taking a course, but also operating within a professional environment.

Beyond the technical content of the course, a number of administrative factors were addressed by taking a people, processes, and tools approach. The challenges mirror those faced by medium to large companies upgrading to a new enterprise system. The stakeholders involved include the course instructor, the support team (i.e., teaching assistants and graders), IT personnel charged with supporting the technology, and industry advisors.

The support team is comprised of nine graduate students – who serve as teaching assistants – and five undergraduate graders. Graduate teaching assistants play a critical role in the course. They interact with students during lab sessions, provide feedback, hold office hours, and are in charge of grading and email communication. All teaching assistants were interviewed and evaluated on their experience with engineering processes, CAD, and their ability to lead and instruct in a classroom environment. The undergraduate student graders were recruited from the pool of students that took the course in previous semesters, so they were familiar with the content.

In the first two iterations of the course, each teaching assistant was assigned to four lab sections. However, even with experienced TAs in the classroom, it was determined through student feedback that the ability for a single teaching assistant to manage 20 students in a lab yielded poor response time and resolution quality. Students reported waiting for assistance with modeling issues for 30 minutes at a time, one quarter of the overall lab time, which forced students to regularly seek assistance outside of lab in teaching assistant office hours and email help form submissions, which quickly overwhelmed the support system. By shifting part of the grading responsibilities to undergraduate graders, we were able to assign two TAs to each lab section, which lowered the instructor-to-student ratio from 1:20 to 1:10. The second teaching assistant in the lab performs a portion of their office hour commitment during lab time to reduce the load on the traditional office hours.

University IT played a critical role in the transformation of the course in terms of the systems integration between CAD and PDM. With a long history of working with this type of applications at the university level, the IT staff were well versed in deploying and maintaining PLM systems. However, each new implementation has its own unique challenges, which were largely overcome by partnering with the software vendors and industry experts who provided guidance and support on how to properly configure the systems for classroom use. For example, the PDM system must be reset each semester to the starting configuration and the connection between the CAD and PDM system must be set up such that students can install and run it from their own personal laptops. The relationship between faculty, IT support, and industry partners and advisors has been a key component to the success of the transformation of the course.

In terms of technology, the tools utilized to demonstrate competency in the course are the CAD package Siemens NX and an enterprise PDM system known as Aras Innovator. A CAD connector provided by Essig PLM provides NX and Innovator with a direct link in the form of an NX add-on so users can save and retrieve part models and assemblies from the PDM server directly from the CAD interface. Both NX and Innovator are configured in a manner that ensures a smooth and seamless workflow in the course and standardizes the work that students submit, much like an enterprise deployment. Since student data (including files, assignments, grades, and feedback) must be stored in the PDM system, University IT had to review the PDM system, user security, and server configuration to ensure it was FERPA compliant and that individuals without FERPA access could not access student data and students could not see each other's data if not explicitly required by the course.

In terms of processes, nearly all course procedures were redesigned to better deliver and manage the content and to support students, particularly with issues related to the industry tools and processes required to complete and submit the assignments. Using enterprise tools like PDM instead of a traditional Learning Management System created technical challenges for students and instructors. The issues, however, were no different than those faced at large original equipment manufacturers (OEMs) as they roll out new enterprise systems to their workforce. In just the same way a company would build a deployment strategy to train and support their workforce, policy and procedures had to be set to support not only content questions, but also technical support questions.

The initial deployment of the PDM system with CAD in the course revolved around the PDM connector with the CAD system. Initial assignments centered on how to store and retrieve data to and from the PDM system, as shown in Figure 1. Assignments are submitted for review by the due date by manually promoting the corresponding items in the web interface of the PDM system to a state of "In Review," as shown in Figure 2. The items must be placed on an Engineering Change Order (ECO) and sign-off by the student as "complete" through a workflow that mimics a formal change process.

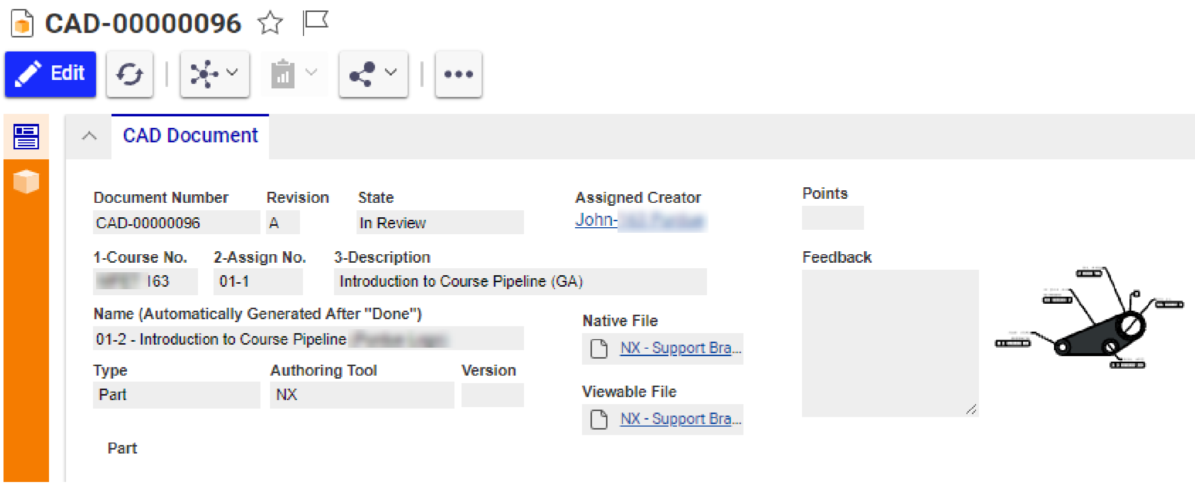

Figure 1. Assignment submission form.

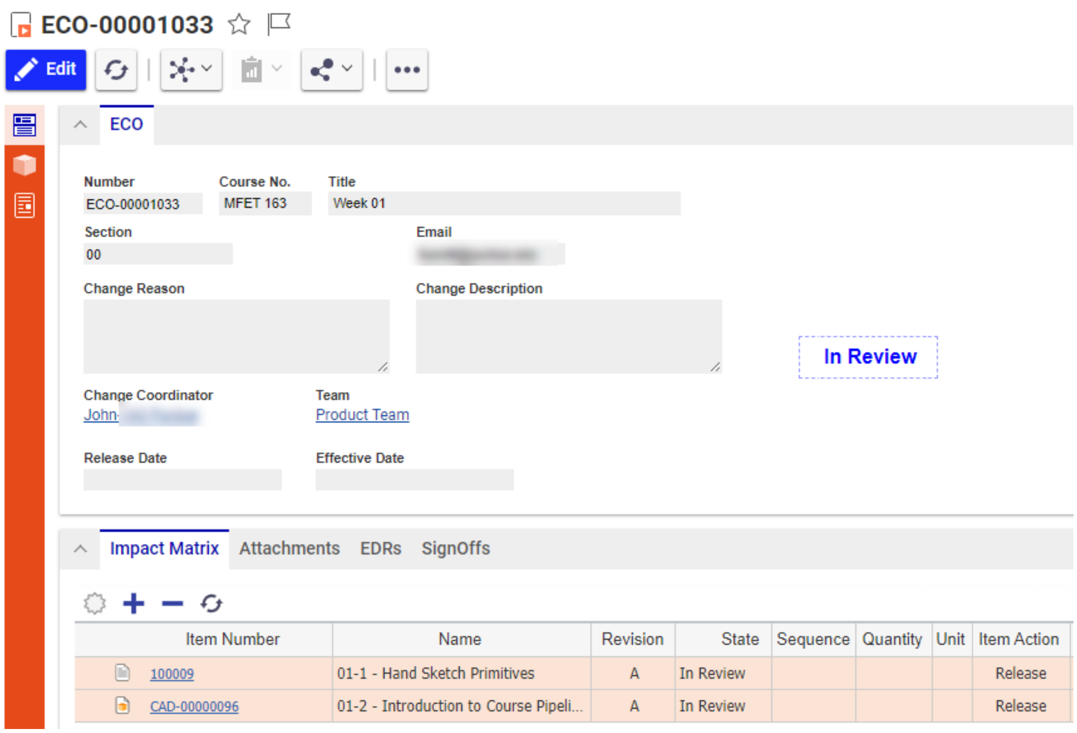

Figure 2. Item promotion to "In Review."

Once in the "In Review" state, the instructional team grades the items stored in the PDM based on the "Last Modified Date" to ensure it was submitted by the deadline. After providing a score and individual feedback, the item is then promoted to the state of "Released." Scores are then exported from the PDM system and imported into the university LMS. Feedback is published to each completed item in the PDM system to mimic a design review process. An example is shown in Figure 3.

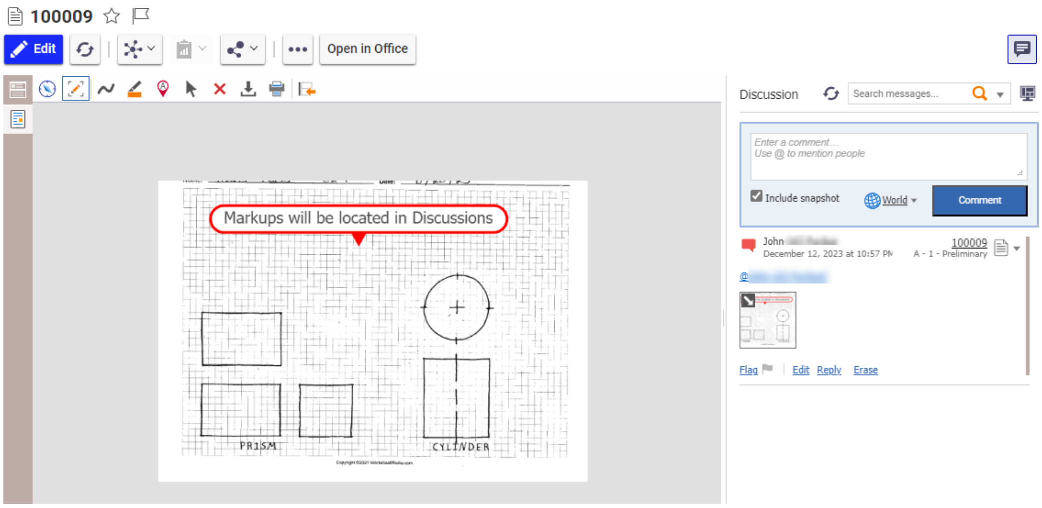

Figure 3. Assignment feedback in the PDM system.

To address the technical and process related issues, a support model was developed to create functional and manageable lines of communication between students and the instructional staff. Historically, each teaching assistant was assigned to a set of labs and thus responsible for helping the students in those labs via email and designated office hours. With the volume of students in the course, it was determined that implementing a help desk model was necessary to ensure timely accurate responses to all student inquiries. Students are encouraged to review class materials and interact with other students before contacting the instructional team. The flow diagram of the process is illustrated in Figure 4.

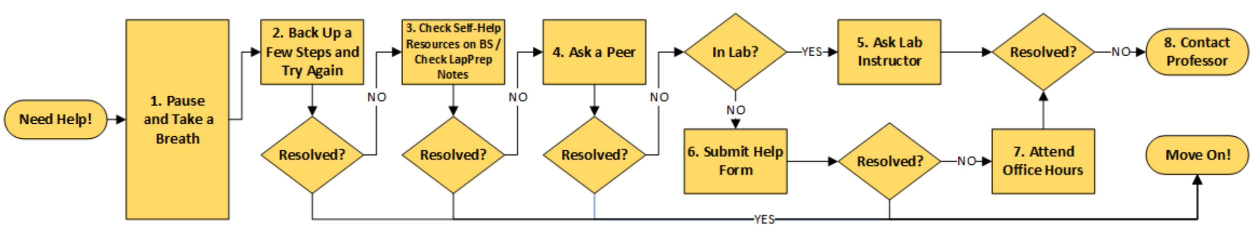

Figure 4. Flow diagram for the support model implemented in the course.

Frequently asked question scripts were also set up to allow teaching assistants to quickly answer common questions. A form was developed to capture important information such as the type of issue, description, and any supporting screenshots to reduce the time and effort required to provide assistance. The form feeds a course email inbox created to funnel all student inquiries to a central location where teaching assistants could work as a team. A section of the form is shown in Figure 5.

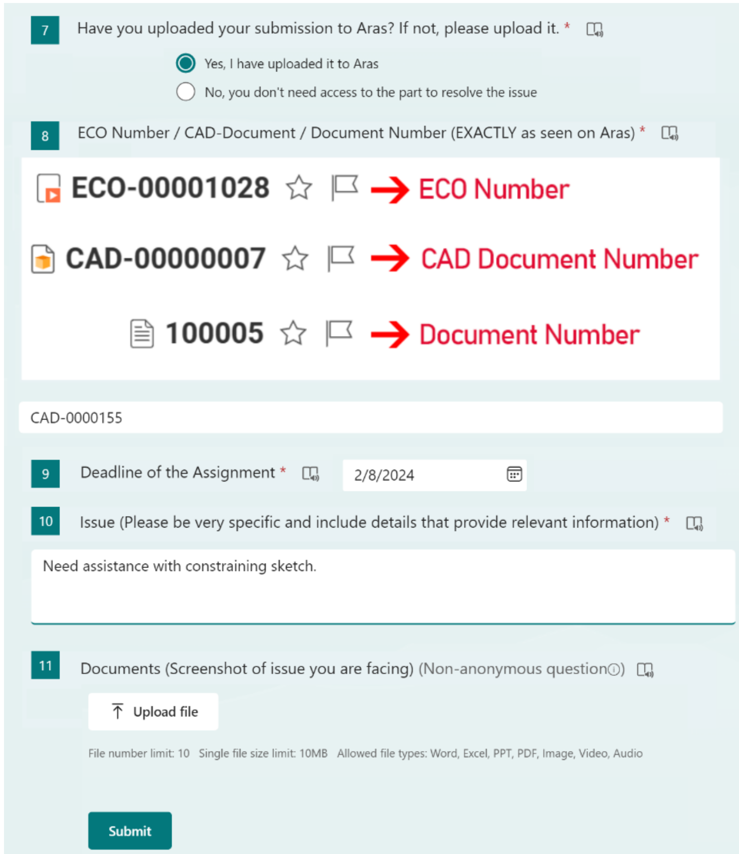

Figure 5. Section of the issue report form.

Discussion and Lessons Learned

After two semesters of manually promoting items in the PDM system, the use of PDM evolved to associating those items to more complex items with additional metadata, which required further instruction. The concept of parts and ECO sign-off proved difficult for many students to grasp in the context of a course with a main focus on modeling. Technical difficulties with the CAD connector also appeared in software being loaded on student personal computers and improperly configured university machines. For these reasons, a number of students were spending more time attempting to release items and submit their work than they did to complete the actual modeling work.

To address the previous problems, the third semester of the implementation found the course simplifying the concept of items in the PDM system, but still employing the ECO sign-off process for release. Additionally, the CAD Connector was removed from the process and replaced with instruction on manually uploading and downloading data from the PDM web interface. The simplified process significantly reduced technology problems and was later used to illustrate what a CAD Connector does behind the scenes, so students can revert to a manual process if the CAD Connector has connectivity or synchronization issues.

One key element in the implementation of PDM was instructing students that a PDM system is not like a university LMS. Initially, students only stored their data in it when they were ready to submit. When this came to light, we emphasized PDM as a collaboration tool and that the data should live there once created. It was further explained that this approach helps the instructional team to provide feedback before submission deadlines and ensures that the student data is in a location that can be backed up and recovered.

The grading process for the course was notably improved with respect to the original format. In the original version of the course, grading occurred within a given lab section via screen grading. Students would pull their completed models up on the screen and TAs would visit each student individually to grade and provide feedback to the students on site. With approximately twenty students per section and three to four assignments per week, the grading process encompassed most of the lab time, which did not leave any time left for students to receive guidance on the following week's assignments. However, allowing teaching assistants to grade assignments outside of class also came at a cost. In some cases, feedback was not being returned to students for two to three weeks at a time due to the volume of work generated in the course and thus students repeated the same mistakes week after week before they received feedback. To address this issue, due dates were adjusted and five undergraduate students were onboarded to turnaround grades and feedback by a student's next lab session.

One major procedural complaint with the course was the amount of time it took to complete assignments and lack of time to do so. To address the time allotted to complete assignments they were all made available for a three-week period and all sections work due on the same day each week, Friday at 11:59pm. One week before the assignment was set to be completed in lab, the week it was to be worked on in lab, and one additional week to allow for completion before it was due. However, we observed that, regardless of the amount of time provided to students to complete assignments, the majority waited until the last 48 hours to complete the work. In response, a 10% extra credit was given to anyone that turned the work in the week that the work was to be completed in lab. The incentive was not widely taken advantage of by students though. Having all sections of the course with a synchronized due date also caused issues with server response time when overloaded with students attempting to submit work all at once. It was determined that the default setting in the PDM system configuration and SQL Database limited the number of active threads. The problem was initially mitigated by moving the due date to Saturday morning at 7:00am, which alleviated some stress on the system. With the knowledge that students submit work within 48 hours of the due date and to reduce server load, due dates were moved to correspond with the student's lab day and set to 11:59pm that night, which gives them three lab periods to work on an assignment if they fall behind. A late submission period was also instituted with a 30% penalty for the following Monday at 11:59pm.

Conclusion

The course transformation and software infrastructure described in this paper represents a step forward in the development of a digital enterprise curriculum that emphasizes data management. Not only has our approach moved the needle in terms of level of understanding of how CAD and PDM fit into the digital enterprise, but many students returning from internships after taking the course have enthusiastically expressed the relevance and practical aspects of what was leaned in the course in relation to the responsibilities and duties performed. Having a foundational knowledge of the tools and processes sets engineering students apart from their peers and provides the employer with a young engineer already familiar with the tools and processes used to design and develop products, not only the theoretical principles.

To ensure a successful implementation, however, our strategy requires a phased approach, with support from IT and industry partners, a fully engaged and committed instructional team, and a continuous improvement culture in an environment that allows a basic level of autonomy and ownership among the teaching staff. Changes and reasons for change must be clearly communicated to the students as they are stakeholders in the process and need to know why things change, just as they would in an industry setting to foster support for the change rather than frustration.

In the future, we plan to distribute assignments as sets of requirements in the PDM system, which students must meet and link their file to, thus introducing the students to additional more complex digital thread concepts. The use of the PDM system also enables the integration of other engineering systems. For example, ITI CADIQ can be employed to detect and report on model integrity, which can assist in the automation of grading. Custom scripts can also check model history to detect plagiarism when the models are submitted to the "In Review" state and provide detailed reports and flags on the specific items. In addition, we plan to incorporate the set of grading rubrics used in the course, which are currently in the form of highly automated spreadsheets, within the PDM system to reduce the number of software applications and programs required to score and report feedback. Finally, we intend to test the benefits of dashboards to track real time submissions rates and build a connection via APIs to feed raw scores in the PDM system to the LMS of record which is currently done manually via Excel.

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