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Application of Extracurricular Course Teaching Product Lifecycle Management Concepts to Undergraduates

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Abstract

Extended, project-based activities are critical for preparing undergraduate students for roles in modern industry yet are often difficult to provide through traditional curricula. This practice paper describes the objectives and functions of a student-centric research endeavor within the Clemson University Creative Inquiry framework that provides guided instruction and extracurricular experiences on product lifecycle management (PLM). The course objective is to develop a digital twin for a scaled, tracked, robotic vehicle while introducing participants to PLM topics and tools. Due to its breadth, this project incorporates activities such as collaborative design and project management, while providing hands on experiences with computer aided (CAx) tools, organizational documentation, and additive manufacturing. Relatedly, students are empowered to explore PLM topics of individual interest, gaining insight into the digitalization of STEM fields. Observed challenges include participant turnover and maintaining the relevancy of the project through strategic updates. The course showcases the value of extracurricular projects in preparing undergraduate students for successful roles in industry.

1. Introduction

As a catalyst and support of the Third Industrial Revolution (the digital revolution), Product Lifecycle Management (PLM) technologies have served as core components of many companies' digital strategies for years. Today, PLM continues to drive digital innovation and advancements as part of the "epi-digital" nature [1] of the Fourth Industrial Revolution (4IR) [2]. A lack of knowledge of proper utilization of these technologies can drive inefficiencies and cause difficult problems for engineering organizations. Traditional engineering curriculum has responded to the advent of digital technology, incorporating instruction time with computers, programming, and application usage [3]. Despite this, PLM remains limited in exposure to undergraduate engineering students, who graduate with less than ideal proficiency in PLM topics such as informatics and change management [4].

The lack of PLM topics in engineering curricula was discussed as early as 2004 by Frame et al. [5], who mentioned that PLM is best introduced in relation to the holistic design of a product, covering its entire lifecycle. Frame et al.'s solution was to include usage of PLM software throughout the undergraduate program of study however, this solution is unable to provide the continuity of following a singular product. Another approach is the formation of an extracurricular project group focused on providing undergraduate students with hands-on experiences using PLM tools in a structured environment that simulates a typical industrial utilization paradigm through providing employee roles, structured workflows, collaborative projects, and formalized review processes. This approach is similar to that taken by Fradl et al. [6], who divided their instruction of PLM into three parts: working with the product, establishing relevant business processes, and utilization of modern Information Technology (IT) tools. The project group is tasked with creating a digital representation of a robotic, tracked vehicle, a project that requires a diverse number of tasks suitable to experiencing PLM technologies in a variety of relevant sub-projects. An overview of this course is shown in Figure 1.

The structure of this extracurricular course is depicted in this article for the purpose of communicating fundamental aspects of the project group and their effect in helping participating students learn PLM tools and processes in preparation for future roles in industry. Though industrial cohesion is impossible to measure (due to the lack of samples), technical skills are measured through projects that demonstrate a student's proficiency with the various software tools. This extracurricular course follows a Project-Based Learning (PBL) approach to teaching PLM, which has found success in other similar programs [7]. The PBL approach is demonstrated by fostering relevant experiences showcasing the utility, functionality, and application of PLM concepts.

The remainder of this paper is organized as follows: (a) reasons and motivation for teaching PLM, (b) description of the establishment of the extracurricular course, (c) definition of the course and its central project, (d) how the course is structured, (e) various activities and methods used in the course and their effects, and (f) discussion of the course and some possible concerns.

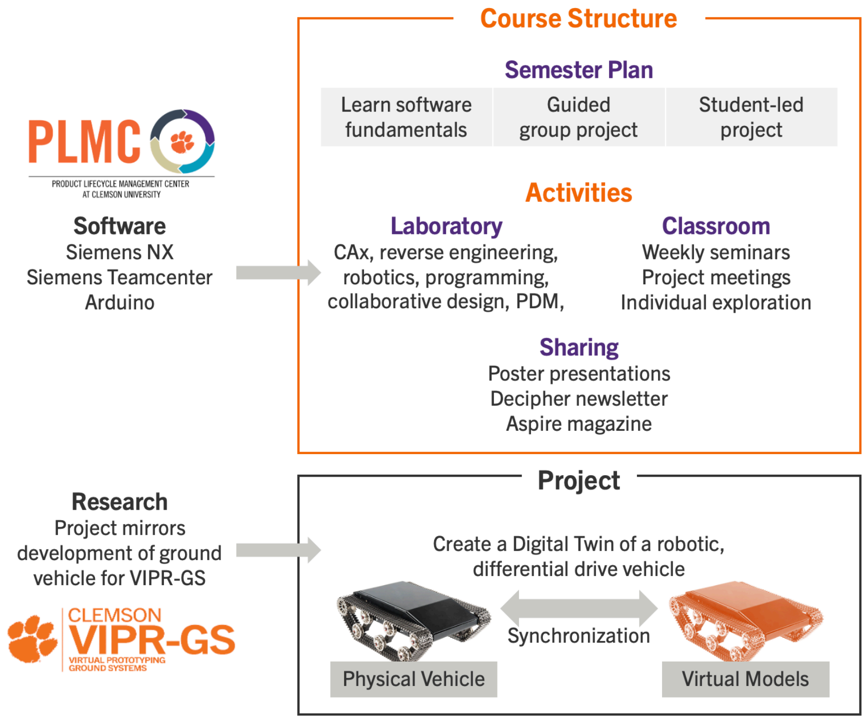

Figure 1: Overview of project group structure and activities.

2. Motivation for teaching PLM

The prevalence of 4IR discussions has made the subject nearly cliché, though the topic is not dismissible when considering the trajectory of modernizing industry. Central to the 4IR, and of indistinguishable importance, are concepts of digitalization such as data-driven processes, informatics, networking, and automation. The revolutionary nature of digitalization is driven by the continual advancement of computer technology, which has broadened access to critical technologies enabling digital concepts. Examples of this transformational disruption include access to mobile computing devices and global internet access enabling cloud computation, and the cost of informational storage depreciating in concordance with Moore's Law.

The 4IR has also been supported by and given rise to many software applications, the development of which has been critical to digitalization across all industries. Learning these applications have become prerequisite to successful employment for many workers, who must learn to expertly administer the digital tools driving the digital revolution, just as workers had to learn the physical tools driving the first Industrial Revolution.

For engineering programs at four-year universities, the need to teach the additional technical skills required by the 4IR is a significant burden. Traditional engineering curriculum typically attempt to blend theoretical knowledge, following the disciplines of mathematics and the sciences, with practical skills. Mechanical engineers, for example, might take courses in mathematics, physics and design supplemented with laboratory experiences teaching programming, machining, and Computer-Aided Design (CAD). The results of these curricula are engineers with a broad understanding of many subjects, with some applied skill sets. However, the number and complexity of courses required for successful establishment in industry makes engineering programs the longest programs in universities (as measured by credit hour). Johnson et al. [8] found that among undergraduate programs in the United States, the five programs with the highest median required credit hours were all engineering programs. Because of these longer program lengths, it can be assumed that universities struggle with incorporating additional courses targeting the many new technologies developed in concordance with the 4IR, despite their relevancy to real-world industry. This challenge is especially significant given the increasing need for competent engineers supporting the 4IR [4].

One core domain of interest is PLM, an umbrella term that has been provided many definitions by diverse interest groups. This paper employs a definition of PLM as the tools and processes utilized to manage product information throughout a product's lifecycle. This definition is broad enough to include CAx software (such as CAD, Computer-Aided Manufacturing, and Computer-

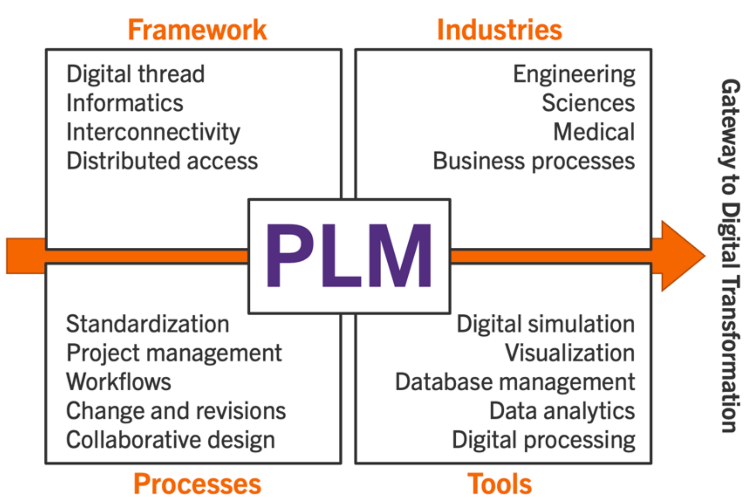

Figure 2: Overview of Product Lifecycle Management (PLM) elements.

Aided Engineering) as well as Product Data Management (PDM), Engineering Change Management (ECM), and Project Management. PLM was fundamental to the digital revolution (alternatively referred to as the Third Industrial Revolution) and continues to play a key role in the 4IR, where it is often the backbone of an organization's developmental and deployment processes. An overview of the impacted areas and constituent domains of PLM is shown in Figure 2.

Despite its widespread adoption and essentiality to the 4IR, the preexisting length of most engineering programs proscribes the inclusion of additional classes focusing on PLM. This results in PLM being a largely unknown subject among undergraduate classes. Informal polls among senior undergraduate mechanical engineers at Clemson University, in the Southeastern United States, showed less than 10% of students had heard of PLM by the last semester of their program. Though not intended to be conclusive, this observation can demonstrate the lack of focus on PLM within a traditional program.

3. Initiatives for Teaching PLM

To increase understanding of PLM tools and processes, Clemson University instituted the Product Lifecycle Management Center (PLMC) with the mission to "foster learning environments through dedicated laboratory(s), workshops, and industry outreach efforts for education . . . research . . . and demonstration of product applications" [9]. The activities of the PLMC include research into improving utilization of PLM tools, championing PLM within local industry, and educating students about these critical concepts. The "dedicated laboratory(s)" operated by the PLMC provide Clemson University students, faculty, and staff access to a number of PLM applications, as well as training for how to use them.

To promote these tools, and the processes driving their usage, the PLMC hosts weekly seminars teaching unique PLM topics and workshops showcasing the various programs. These seminars, supplemented by additional guest presentations in more traditional classroom settings (as shown in Figure 3), provide exposure to an array of PLM concepts; however, mastery of PLM technology generally requires interactive learning experiences that provide students with the opportunity to interact and explore PLM applications.

Figure 3: Image of seminar conducted by the Product Lifecycle Management Center for sophomore engineering students.

One solution for teaching PLM that avoids extending engineering programs is providing it as an extracurricular activity. This paper presents a case study of a semi-extracurricular project group designed to teach PLM to undergraduate engineering students. The project group is an elective, reoccurring, semester-long class project that has been running for two years and enrolls, on average, six participating students per semester. It is sponsored by the PLMC and utilizes all the resources presented and housed by the center, as discussed earlier.

Students in the project group receive one credit hour per semester of attendance, which corresponds to an expectation of three hours of time to be spent out of class, another hour spent doing collaborative projects with other students, and an additional hour attending seminars discussing PLM concepts. Though students may be from any department, the focus on the course most appeals to STEM pathways and especially from engineering majors.

4. Course research project

The project group is sponsored by Clemson University's Creative Inquiry program as part of its focus on undergraduate research. As a research-oriented activity, the project group differs from a typical lecture-based class, especially regarding its overall objectives. Though the purpose of the project group is to teach students about PLM processes and tools, the course objective is the design of a complex digital representation of a robotized, differential-drive vehicle distributed by Dagurobot (shown in Figure 4). Having a discrete research objective is a benefit to the overall group purpose, allowing the class to blend both theoretical concepts learned in lectures with their practical application to the course project.

The digital representation is better termed a digital twin (DT), a combination of virtual models and data streams synchronized with the robotic vehicle. DTs are used in many industries to represent (or twin) the behavior, characteristics, and states of real-world entities with greater precision and fidelity in a virtual domain. The end result is a digital recreation of the physical entity that behaves analogously its counterpart. Though their varied uses give them conflicting definitions [10], the digital twin is an important concept of the 4IR, with especially high importance to manufacturers [11]. The creation of a DT is a complex task involving modeling, simulation, and data connectivity and processing, in tandem with the complexities of working with the mechatronic vehicle system.

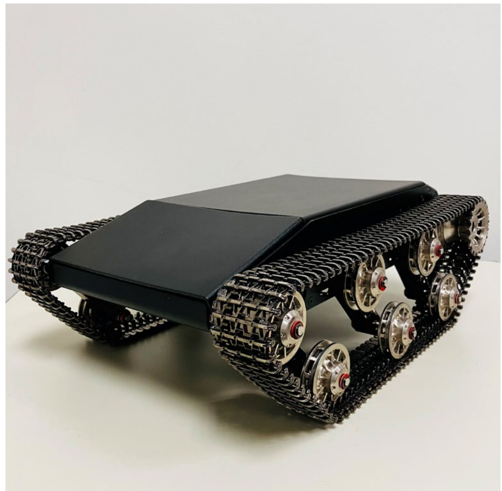

Figure 4: Photo of the robotic, differential-drive vehicular platform.

In conjuncture with the research objective of building the DT, the course has additional objectives of teaching students complex industrial-level PLM applications for CAx and PDM. All geometric models are created and managed using Siemens NX, a PLM software, while document management is enabled through Siemens Teamcenter, a PDM application. Students spend the first three weeks of the course getting familiar with the software, following learning modules to help them acquire the necessary technical knowledge. These software applications are then utilized throughout the remainder of the class, allowing increased understanding with the applications' complexities.

This is especially true with PDM. A DT requires tight collaboration of information and the establishment of a robust digital thread. In the beginning of the class students learn how to use Siemens Teamcenter (as the main source for PDM), and then must employ Teamcenter to maintain the integrity of the DT throughout the remainder of the semester.

The motivation for the project stems from Clemson University's Virtual Prototyping of Ground Systems (VIPR-GS) Center, who, in partnership with the United States Army Ground Vehicle Systems Center (GVSC), aims at "developing innovative virtual prototyping tools for designing the next generation of on- and off-road vehicles" [12]. The research project includes fabrication of several differential drive vehicles which are used for validating research in autonomy, energy management, propulsion, and digital design. These vehicles, such as the one shown in Figure 5, are designed and fabricated by the Deep Orange team, a unique vehicle prototype program at Clemson University. The robotic platform to be twinned by the project group embodies the major elements of an off-road, differential-drive vehicle and is a simpler abstraction of the more complicated system. In theory, models and simulation tools developed for the robotic platform can drive further innovation for DT development of the larger vehicles developed through VIPR-GS.

Figure 5: A custom designed and fabricated off-road tracked vehicle developed through by the Deep Orange team in collaboration with the VIPR-GS Center at Clemson University.

5. Course structure

Though PLM initiatives largely originate within engineering departments, PLM concepts and tools can be used by and impact every working group in a company. Because of this, the undergraduate course is made available to students of all disciplines, though the course description draws students more inclined towards technical research. Majors of enrolled students have included mechanical, civil, industrial, electrical, and general engineering.

The project group has a deliberately devised structure intended to encourage students' abilities to both learn and apply information about PLM. There are four major components to this structure: (a) weekly seminars presenting theory, (b) collaborative project meetings, (c) guided projects, and (d) student-led projects.

1. Weekly Seminars

Each week students attend an hour-long seminar about a specific PLM topic such as revision management, data mining, or additive manufacturing. The lectures are curated to cover the fundamentals of a broad set of topics, serving as starting points for further exploration. Though presented in person, these seminars are also available as recorded, asynchronous lectures, which students can watch at their own pace. Making the seminars available virtually allows students greater flexibility in learning the material, a worthwhile objective given the busy curriculum most of the students are enrolled in. Brief reviews of the seminars are offered during the weekly class meetings, allowing students to reflect on the material and ask questions in person.

2. Collaborative Project Meetings

These weekly, collaborative meetings allow the class to visit about course objectives and discuss assignments in connection to the overall class project of developing a DT of the robotic vehicle. Though learning is largely an individual effort, industrial development taskforces are generally collaborative in nature. This group functionality is simulated through these weekly meetings, where students work together to complete group objectives such as designing engineered systems.

The type of activities requisite in building the DT is diverse enough to allow for multiple projects to be carried out simultaneously, but of sufficient succinctness to require tight integration and collaboration between individuals. This allows students to work on projects according to their own interests, while also providing avenues for learning collaborative skills such as file distribution, storage, ownership, and access.

3. Guided Team Projects

The middle part of each semester (about five to six weeks) is allotted to a guided project that enlists the entire class. Past projects have included reverse engineering the robotic platform, developing an odometer for measuring vehicle motion, and creating a sensor rig to house additional electronic sensors. These projects have shorter time scales than the overall development of a DT, allowing students to experience a complete project from start to finish. By assigning tasks and working within a group, students also experience a representation of an industrial development group. In this concept, the class instructor is the project manager, and each student might be assigned a variety of roles that may be dependent on the tasks of other group members. Experienced students are given additional leadership roles as well in these groups.

While students generally have experienced group work in other classes throughout their undergraduate studies [13], working in structured groups such as this allows them to experience groups that more closely mirror professional departments. This emulation also enhances students' perception of the relevancy of the PLM systems they are learning about, giving them the ability to make connections between facets of the software they are using and the projects they are working on. For example, Figure 6 shows two students working together to create a PCB board for an odometer designed and fabricated by the students in the course. In addition to learning electronic prototyping skills such as soldering and circuit design, students created a series of solid models using Siemens NX with established interfaces that were maintained via a custom Product Data Management (PDM) program.

Due to the breadth of the project, there are many niche activities that students can participate in. For example, in the Autumn of 2022, students worked together to create an odometer to measure vehicle motion. One group of students was assigned to design and create the sensor-board, soldering integrated circuits (IC) onto a prototyping circuit board (PCB), while another group worked on designing and assembling a plastic housing manufactured via a Fused Deposition Modeling (FDM) machine. Near the end of the project, students from both groups were taught by their peers in the other group about the work they had done, with the two groups combining to both print the designed housings as well as troubleshoot the electronics system.

Figure 6: Students working on the mechatronic system of the robotic vehicle as part of a guided project.

4. Student-Led Projects

The last few weeks of each semester are provided for students to choose their own project to work on, either individually or within self-assigned teams. These projects must still contribute to the overall development of the DT but can be uniquely defined by the individual. Examples of past projects include developing programming libraries for the robotic microcontrollers, extracting physical constants via controlled experiments, and making comprehensive models of the vehicle's geometry.

To select their project, students work with the class instructor to see how they can further the development of the DT while simultaneously exploring a topic of their own interests. Some students choose to continue cultivating skills with a specific software, while others opt to learn an entirely new skill. The success of the student-led projects is derived from the diversity of work necessary to create the DT, which encompasses mechanical, electrical, and computer engineering, as well as data science and business processes. Ideally, this diversity makes available projects that are engaging for a variety of students across science, technology, engineering, art, and mathematics (STEAM) disciplines.

6. Results

Over the last four semesters the course has operated, several successful methodologies have emerged. Because the class is not a traditional, accredited course it is allowed greater flexibility in its structure and practices. This increased flexibility has allowed for experimentation with an assortment of systems that has allowed for some optimization in the course structure, as well as the exhibition of less desirable practices.

One such optimization is in the number of student participants. The nature of class prohibits large class sizes, or even likely normal class sizes (20 to 30 students). Smaller class sizes allow for more one-on-one work with the instructor, as well as close collaboration with other groups. Wheelan proposed that groups of nine or more participants perceived less focus on the group project, while groups of three to four may outperform groups of five or six persons [14]. The class size of this project group has been kept under nine individuals, and in large groups has been broken into smaller taskforces of one to four individuals. The small overall numbers allow for meaningful participation of students with the instructor, while the even smaller group sizes permit effective role distribution, allowing each student to engage on the assigned task.

The students' proficiency with PLM software applications (such as CAD) was difficult to measure using uniform evaluations. This was due to the nonhomogeneous skill levels of participating students; a freshman in bioengineering is unlikely to gain the same proficiency with CAD software as a senior in industrial engineering. Observations from the students' design projects indicated that students with previous, collegiate experience with PLM applications were more successful at learning new software.

A largely successful way to provide formative feedback was through design reviews with the instructor. Since many of the sub-projects in the course require system, model or part designs, each student is required to go through a design review of their work with the instructor. This allows the instructor to give them immediate feedback on their work, helps the student recognize both the correct and incorrect aspects of their work, and gives them the opportunity to make corrections. The design reviews are short (on the order of 15 minutes) but create avenues for the instructor to teach advanced skills in modeling or simulation as needed by each individual. With design reviews in place, students can also work more independently. Here the design reviews function as check gates, allowing students to explore and develop their work, with the understanding that they will have later opportunities to verify the validity of their contribution.

Finally, the nature of the DT project has been critical to the success of the project. This is likely due to two factors: the diversity of a DT and the relevancy of a DT. The first item, diversity, encapsulates the varied number of tasks needed to create a DT. The diverse subject material allows for incredible flexibility in the course. One semester of the course focused almost exclusively on solid modeling in Siemens NX, due to the experience and desires of the students, while another incorporated microcontroller programming, reverse engineering, requirements mapping, and dynamic simulation.

The second reason for the success of the project is the relevancy of the DT. Though diverse, the DT is a uniquely technical project that encourages students to acquire practical skills immediately applicable in industrial roles. These skills are not abstract, but neither are they impractically narrow. Finding this middle ground between generality and specificity is important in consideration of preparing students for future contributions in industry. Though industrial functions require specialized skills, it is impossible to predict the exact skills needed by every student in a university program due to the number of possible career paths available to each student, each requiring different technical knowledge. By providing students with general knowledge applicable to a wide diversity of PLM processes, students are better equipped to specialize according to their own interests. They are also better suited to excel in any arbitrary role, having previously understood the basic, common functions of many different tasks.

7. Discussion

The project group is an effective way to provide semi-extracurricular instruction in PLM to undergraduate STEM students, as demonstrated by the practical and theoretical skills acquired by the participating students. These skills include electrical prototyping, solid modeling with

Siemens NX, additive manufacturing, robotic systems, product data management, collaborative design, sensor configuration. Future semesters will also learn networking, database management, and virtual simulation.

Throughout the evolution of the course, several concerns have also arisen; inspecting these concerns can help evaluate the effectiveness of the project group. Foremost of these is the ability of such a small group to impact the larger student body. Though the seminars presented by the PLMC are offered to large groups, the reach of the project group is an average of seven students per semester. Possible expansion of this reach could be accomplished by running multiple courses in parallel, albeit at the expense of employing additional instructors.

The other concern is that the reality of the project of creating a DT requires a progression of tasks that must follow some sort of chronological timeframe to culminate in the finished product. An arbitrary project with no real-world connection does not have to follow such a timeline; tasks can be repeated or delayed into perpetuity. There exists some gradient between the unbounded flexibility of an abstract project versus the bounded development of a research project with real-world applications. Though this project group has attempted to strike a balance between the two extremes, there is concern that, in coming semesters, the DT project will require tasks and steps that are difficult for new students to complete without having continued with the project group throughout the entirety of its track.

The problem of chronological dependency and task flexibility is compounded by the capabilities of the students, which must be developed through training with the utilized PLM applications. Though the class is focused primarily on teaching PLM, successful completion of the tasks necessary to create the DT requires mastery of the respective skills associated with each task. The current solution is to allow the instructor flexibility in determining the time given to participating students to practice the requisite skills before requiring completion of a given task.

Future work will focus on evaluating the effectiveness of this course. Possible methods of evaluation might include measuring students' usage of PLM in senior design classes, as well as skill tests measuring growth in technical skills throughout the semester.

8. Conclusion

It is important for undergraduate engineering students to deliberately prepare not only for their roles as engineers, but for the skills and technological developments expected of them in a rapidly evolving world [15]. Though commonly the longest curriculums by credit hour, engineering programs need to find ways to include instruction concerning digital technologies underpinning modern engineering. An example of a valid approach is an extracurricular project-oriented group that allows students to gain hands-on experience working with PLM tools in a guided emulation of an industry work group. The example of such a project-based class provides valuable demonstrations of some critical elements of such a group, including a diverse and relevant class project, dedicated teaching of PLM concepts, software training, guided projects utilizing PLM processes, and student-led projects allowing individual exploration and specialized, personal development. The possible value of this class can be quantified in coming years through surveys that seek to measure the preparedness of each student for their careers in industry.

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