Application of Product Lifecycle Management in the University Classroom and Laboratory

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1. Introduction

Product Lifecycle Management, otherwise known as PLM, has emerged as an essential process and tool suite for a wide range of companies across the globe [1]. The adoption of digital design and manufacturing processes can accelerate the product development cycle and enable greater product functionality and features. The growing use of PLM worldwide has generated a need for engineering and technology graduates with basic knowledge and experience in this area. By integrating the software and accompanying process paradigms into the curriculum and/or offering supplemental PLM software workshops, students can join the work force ready to contribute with their virtual designs [2]. Companies will be able to depend on recent graduates to immediately step into more responsible technical roles due to a background in PLM software and strategies. Not only will this benefit students as they will be able to integrate themselves into the company quicker, but businesses will be able to provide entry level hires with greater opportunities to help the enterprise. An emphasis on PLM skills should increase global competitiveness [3]. The economic success of a company can benefit the workers, community, and stakeholders, and begins with the availability of a talented workforce.

The Bachelor of Science Mechanical Engineering (BSME) curriculum at Clemson University currently uses different software packages to introduce students to Computer-Aided Design (CAD), computer programming, numerical simulations, and experimental data acquisition [4]. As shown in Figure 1, student software use includes MATLAB, NI LabView, Siemens Simatic, and SolidWorks. During the freshman year, the basic features of SolidWorks and MATLAB are covered. Sophomore year, the students learn how to create PLC ladder logic code using Simatic and increase the sophistication of MATLAB algorithms. By junior year, the required courses involve MATLAB coding so that the students can now apply their software knowledge to engineering design problems and simulation projects. Senior year, the students apply the skills they learned thus far to their project oriented and capstone design courses. As Figure 1 shows, space may exist to implement PLM concepts as well as select software packages each year through PLM software workshops for interested students.

Freshman	Sophomore	Junior	Senior
ENGR 1020: Engineering Disciplines and Skills (Excel)	ME 2220: Mechanical Engineering Laboratory 1 (MATLAB, NI LABVIEW, Simatic)	ME 3330: Mechanical Engineering Laboratory II (MATLAB)	ME 4010: Mechanical Engineering Design (Project Oriented)

ENGR 1410: Programming and Problem Solving (MATLAB)	ME 2050: Statics for Mechanical Engineers	MATH 3650: Numerical Methods for Engineers (MATLAB)	ME 4440: Mechanical Engineering Laboratory III (MATLAB, NI LABVIEW, Simatic)
ENGR 2080: Engineering Graphics and Machine Design (SOLIDWORKS)	ME 2060: Dynamics for Mechanical Engineers	ME 3050: Modeling and Analysis of Dynamic Systems (MATLAB)	ME 4020: Internship in Engineering Design (Capstone)
PLM Concepts Seminars	Introduction to NX Software Workshops; Graphical Concepts Seminars	Introduction to CATIA Software Workshops; Graphical Concepts Seminars	Non-Graphical Concepts Seminars

Figure 1: Summary of computer software in the BSME Curriculum at Clemson University and possible insertions of PLM concepts and software tools

The introduction of PLM materials into the undergraduate Mechanical Engineering program can strengthen the computer skills and virtual design process knowledge of students. Freshman would learn about PLM concepts with concepts seminars that offer an overview of digital processes. Sophomore year continues with concept seminars now focused on graphical concepts plus a CAE software package. By junior year, students will have an understanding of how different graphical concepts can enhance the usage of PLM and work with another CAE software. In their senior year, when the students complete design projects, deeper learning opportunities will exist due to their background with different software tools and participation in non-graphical concept seminars. Overall, the students should be better prepared for virtual engineering protocols and tools.

When reviewing the literature, product lifecycle management education opportunities has been offered at various academic institutions [5, 8, 9]. Purdue University (W. Lafayette, IN) offers a certificate program with three courses (30 hours of content each) on digital product definition, product data and configuration management, and enterprise-based PLM [7]. Oakland University (Rochester, MI) prepares students for Industry 4.0 by requiring the use of PLM software tools in their existing Industrial and Systems Engineering Department courses, as well as four specific PLM application courses [10]. An interesting effort has been the K-12 STEM outreach to provide experiential learning. Mid-Michigan Community College (Harrison, MI) provides technology students with CAD/CAM/PLM topics based on a variety of common industry software packages. Product lifecycle management is offered at Chattahoochee Technical College (Marietta, GA) as part of the logistics and supply chain management. Centennial College (Toronto, Ontario, Canada) offers a combined project management and PLM course that introduces students to these concepts within a manufacturing context. Lastly, the Cape Peninsula University of Technology (Cape Town, South Africa) hosts the PLM Competency Center to train students, technicians, engineers and others on these processes and tools.

In this paper, the PLM learning materials and hands-on PLM software workshop topics will be introduced. The remainder of this paper is organized as follows. Section 2 describes PLM, what it is used for, and how it can affect companies in a positive way. Section 3 discusses the PLM Center that has been launched at Clemson University. Section 4 presents the PLM materials, which are grouped into the categories of fundamental concepts, digital product development, non-graphical concepts, and finally, graphical concepts. Section 5 examines how these PLM concepts may be shared with K-12 students using hands on activities and focused PLM software workshops. Section 6 offers two research projects that explore PLM, while Section 7 concludes the paper. The Appendix contains the seminar and workshop student assessment survey.

2. Product Lifecycle Management – Processes and Tools

Product Lifecycle Management is a strategic software umbrella that integrates a variety of different computer tools together to streamline and bolster product development and business management. An underlying PLM strength is the premise of seamlessly integrating and allowing information to be produced, recorded, and stored for later retrieval by stakeholders as shown in Figure 2. In some ways, PLM may be considered an operating paradigm as it incorporates not only the design and possible automatic manufacturing of a product, but also accommodates supply chain management, accounting, field data, etc. that can be used or stored by any sector of the company so that it is available for those who need access. The PLM system has the potential to vastly improve a company's ability to innovate, get products to market faster, and reduce human errors throughout the process [1]. Since this approach is so encompassing, it can become challenging to observe its benefits on a localized level. However, with the corporate work force using a common platform, a company has more control overall across departments. Time delays can be reduced as all data can be rapidly retrieved. For business and manufacturing companies to succeed in competitive environments, stakeholders need to adopt PLM processes and tools. Again, embracing a standardization from start to finish by technical, manufacturing, and business staff will allow for organized compatibility between sectors and enables digitization for the future.

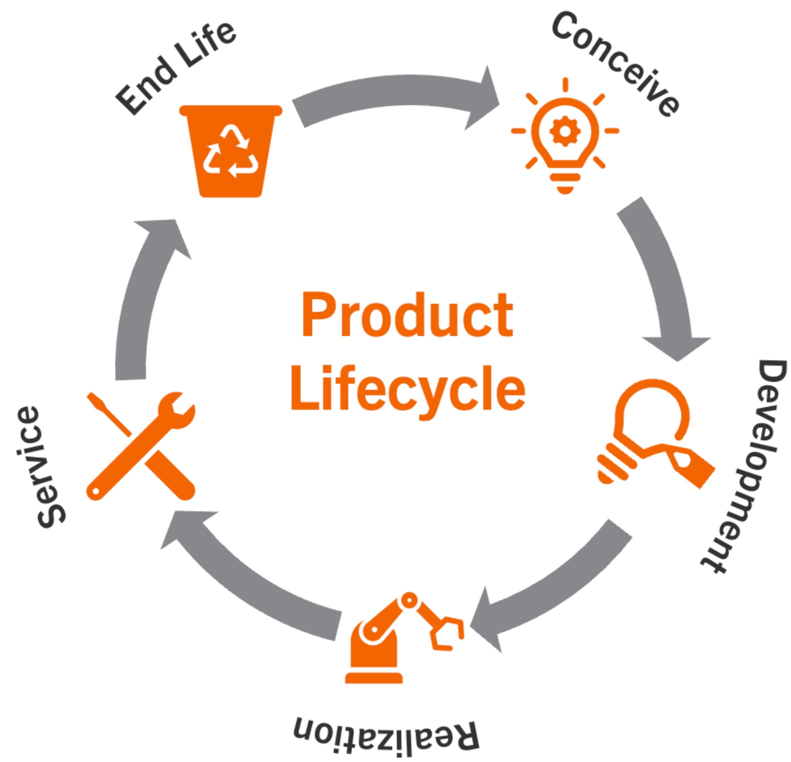

Figure 2: Visual display of the product lifecycle from concept to decommission

For the PLM approach to work effectively, team members must adopt the virtual process and associated tools with databases. The system challenges encompass both the technical aspects of change as well as the people who will be dealing with the new approach [3]. PLM tracks and logs all modifications to a product as it goes through each phase, whether that be with the engineers, marketing team, accountants, sales groups, and anyone else that has a hand in the creation or maintenance [11]. In future situations, those changes can be easily retrieved. This approach enables a post mortem review and opportunity to build upon the design when considering the next generation. For PLM to be fully implemented, it should be introduced into all phases of the company and approved as the standard. By digitizing and working to automate processes, a company can increase productivity and production. Training and networking (refer to Figure 3) opportunities will help workers better understand the role and opportunities that lie ahead for PLM.

Figure 3: PLM networking event where engineers, business leaders, and educators gather to share PLM ideas and directions

From an engineering standpoint, PLM is beneficial as it allows designers to meet required standards and provide specifications for other departments when creating the given product. In the engineering stage, PLM should be implemented as early as possible in the creativity and design tasks leveraging marketing data [11]. The design, analysis, and testing cycle often iterates multiple times before final approval. Ideally, design and development engineers should interact with the product information to properly capture the products operational space and features [1]. Remember that PLM systems support the changes and updates that occur during the planning and design phases, and allows them to build upon older successful designs as well as revert back to previous releases. This rapid flexibility allows for the accommodation of different production methods and supply chain materials to help make the manufacturing system as economical as possible. To manufacture a product, engineering and technology students need a background in geometric dimensioning and tolerances (GD&T). Further, the transition from virtual design to production begins with an STL file, which is then converted into a G-Code using a slicer platform and uploaded into the additive process (e.g., 3D printer) or CNC machines. The continued advancements with computer aided manufacturing enables companies to bring digital processes to the factory floor.

3. PLM Center

Clemson University recently launched the PLM Center for education, research, and industry outreach. Undergraduate and graduate students, as well as industry engineers/technicians, can immerse themselves in the PLM software and processes through class supplements and available PLM software workshops. These learning sessions offer focused training with PLM concepts and technology in the dedicated Computer Laboratory or virtually online. A three-credit hour Creative Inquiry course, for interested STEM students, explores in greater detail the available software packages and their application to vehicle design. These software packages have been generously donated by vendors for academic use. The research activities in the PLM Center help support the academia-industry partnership which addresses common core applications and events. The projects deal with general topics of interest to multiple stakeholders. Further, demonstrations offer industry officials insight into the benefits of virtual engineering tools that can assist with their products. The industrial consortium provides a pathway in which regional companies have access to the education, research, and design advancements at the university and partner technical colleges.

4. PLM Learning Materials

The guidance from industry PLM practitioners has emphasized the importance in understanding the underlying processes as well as the software. To provide students with an opportunity to learn these crucial concepts, the PLMC has developed 16 training modules touching broadly on PLM. These modules are taught in a series of hour-long seminars to students. Interested students from any program can freely attend the seminars, and some classes have offered course credit for participation. Specific modules can also be taught to classes focusing on a single topic, such as senior design classes.

As shown in Figure 4, PLM 1.0 provides an introduction to what Product Lifecycle is and an overview of the various components that contribute to virtual processes. The digital production phase, PLM 2.0, covers product design, data preservation, additive manufacturing, and data analytics. The graphical concepts in PLM 3.0 present computer graphics such as drafting, engineering design, simulation and optimization, and geometric fit. Finally, the non-graphical concepts in PLM 4.0 include project management, handling of product and manufacturing data, engineering change and approval sequence, and the change management process. Together, these four libraries help the student establish a firm understanding of virtual processes and integration opportunities with these tools.

Fundamental Concepts

1.1 Introduction to Product Lifecycle
1.2 Digital Components of PLM
1.3 PLM Functional Areas
1.4 PLM in Practice

Digital Product Development

2.1 Product Design Tools and Approaches
2.2 Data Preservation and Security
2.3 Additive Manufacturing
2.4 Data Analytics and Mining

Graphical Concepts

3.1 Computer Aided Design Methods (CAD)
3.2 Computer Aided Engineering (CAE)
3.3 2D Drawings and GD&T
3.4 System Simulation and Optimization

Non-graphical Concepts

4.1 Project Management
4.2 Product Data Management
4.3 Engineering Change Management
4.4 Systems Engineering and MBE

Figure 4: Inventory of PLM learning materials

The PLM learning materials will be explored in further detail to offer insight into the primary elements of digital environments. As mentioned earlier, PLM 1.0 provides an overview of the entire process including computer-aided design (CAD), -engineering (CAE), and -manufacturing (CAM), as well as engineering data management (EDM) and digital manufacturing (DM) design capabilities. This section starts with PLM 1.1 and a review of past, present, and likely future design practices within the context of product manufacturing. PLM 1.2 examines the digital components associated with product cycles and offers an overview of the advantages to each element and their corresponding role. From there, PLM 1.3 explores the main PLM functional areas which deal with how businesses can integrate themselves into the design process which leads to improved collaborations and interactions between engineers, product managers, and stakeholders to establish core features of the project. Finally, PLM 1.4 considers putting PLM into practice through the creation of virtual products in which students specify the main traits and recommend appropriate processes and tools. Once the foundation is established, the digital production tools are presented in PLM 2.0. Module PLM 2.1 introduces digital workflow processes into existing engineering and manufacturing systems to show how digitalization aligns with and improves upon existing methods. PLM 2.2 manages data preservation and security when transitioning to digital workflow spaces; this process is rigorous and incorporates challenges that are solved by partnering with information technology specialists. Additive manufacturing and 3D printing of parts from existing G-code files is considered in PLM 2.3. The growing availability of additive manufacturing technology enables parts to be created layer-by-layer from sophisticated polymers, metals, ceramics, or composite materials. In PLM 2.4, the application of operating and design simulations are introduced which enables engineers to harvest trends and design issues through micro and macro examinations of information gained from data mining strategies.

Once the groundwork has been established in PLM 1.0 and 2.0, the graphical and non-graphical aspects can be discussed to enhance the student's understanding throughout a product's life. PLM 3.0 presents the graphical concepts where module PLM 3.1 explores the computer-aided design (CAD) aspects of a component to illustrate the advantages of creating online models. PLM 3.2 introduces computer-aided engineering (CAE) methods and explains the common product development practices which allows for greater control throughout the concurrent design cycle. A deeper consideration of two- and three-dimensional drawings and geometric dimensioning/tolerancing occurs in PLM 3.3 with form, fit, and function in analyzing the nominal geometry and its allowable variances in the computer-aided model. Finally, PLM 3.4 considers system simulation of behavior and design optimization. These last materials open the discussion of multi-disciplinary systems and system integrations. Lastly, PLM 4.0 covers non-graphical concepts related to the business processes. PLM 4.1 explores the responsibilities of project managers with an emphasis on project workflow, scope, requirements, and cost, as well as risk assessment. PLM 4.2 considers product data management, where students are introduced to structure configuration management, analysis data management, interoperability, and data exchange. Example applications of the approval and release process where engineering changes are explored and how those changes are propagated and managed through the engineering database to pass the inspection standards are discussed in PLM 4.3. Finally, PLM 4.4 provides an overview of systems engineering, exploring the holistic perspectives of model-based engineering (MBE) and relevant systems modeling resources such as SysML (Systems Modeling Language).

The PLM Center software packages enable students to gain experience, work with prevalent industry computer tools. The Siemens NX software offers a design, analysis, and change update virtual environment for products or assembly. The Dassault Systèmes 3D Experience Library, specifically CATIA, enables three-dimensional design and analysis for given projects. PLM software workshop participants will gain experience with each package to create virtual parts. Through focused short duration concept seminars and PLM software workshops, students and industry members can gain knowledge and background information on PLM processes and tools.

Each area focuses on a series of activities and principles that are consistent with the typical application needed in the engineering field, participants will gain insight into how the product lifecycle management system can be integrated and beneficial in certain aspects. Both on-campus as well as virtual sessions are possible given the digital nature of the materials.

5. K-12 Outreach Materials

To provide community outreach, one effort has focused on the creation of short duration multiple session PLM software workshop materials for middle school students. These software workshops build upon engineering principles while offering hands-on activities for a combination of theoretical and practical applications.

Mechanical engineering is a diverse knowledge field. Mechanical mechanisms were selected as the focal point featuring gears, transmissions, and propulsion systems. First, students learn fundamental concepts associated with gears inducing functions, designs, and manufacturing. The physics behind how a gear works is applied along with the algebraic equations. Next, the students will engage in gear applications such as a transmission. The general operation of the transmission with train ratio. The propulsion system will be examined to show how the transfer of rotational motion with friction enables motion. By the end of the theoretical session, students should be able to explain what gears are and how they are related to different systems as well as understand how frictional forces are affiliated with vehicular applications.

A series of concepts and virtual exercises have been created for CAD/CAE software as shown in Figure 5. The mini-exercises level of difficulty gradually increases each session with the first activity being about PLM and its related software's. Next, the NX modeling software is used to write their names on the back of a pre-existing phone case. In the third module, the students briefly examine the various computer-aided design and engineering tools and apply it to complete the activity of placing gears into a pre-existing part. Finally, finite element analysis concepts and tools are shown and explained for students to get a better understanding of how this feature plays a key role in the CAD/CAE modeling phases for design engineers. The students create their own beam using the modeling software and, if time allows, evaluate the strength and weakness of the designs. Other examples of computer-aided applications will be demonstrated to help individuals gain insight into the possibilities.

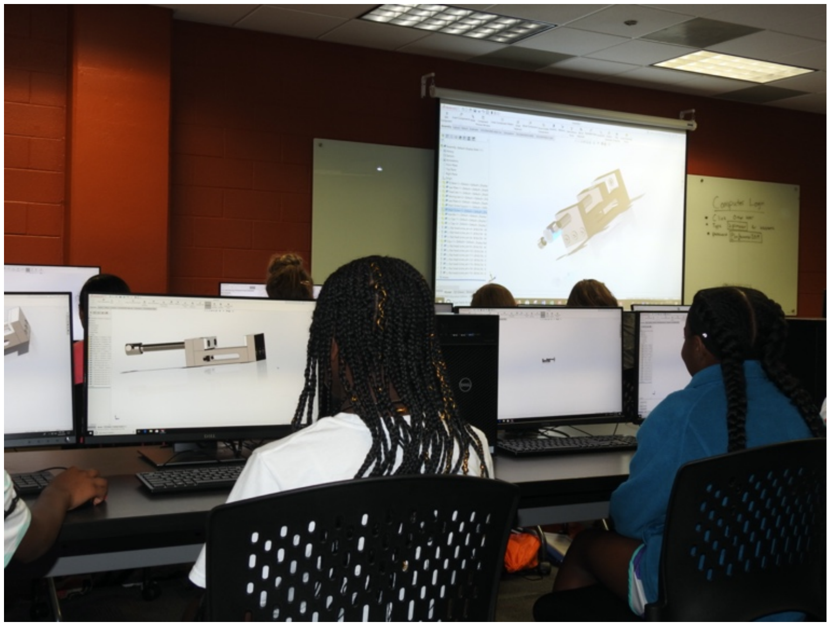

Figure 5: Middle school students participating in a PLM software workshop

The hands-on activities were created to provide students a physical example to accompany the theoretical and CAD materials. Each hands-on activity will relate to something that was taught previously as the first activity deals with the assembly of a gear test stand. The students will be analyzing how different gear sizes change how the system works revealing the concept of torque and efficiency. Once the students have a grasp of how the gear systems work, they will now create their own small transmission system to investigate how it works as well as test improvements that could be made. Next, the students will look into the meshing of gears using a worm gear as the main driving force in the experiment. This illustrates the differences between worm gears and other types of gears as they will incorporate different size gears into the system and observe the torque and rotational changes based placement. The last activity involves friction as students build an axial vehicle. They will apply different loads to the vehicle and measure the pulling force required for that car to move. The testing will start with the wheels that have grooves on them, then move to the smooth surfaced wheels, and finally the wheels will be taken off the system. Each test will allow for frictional observations to be made based on the force required to move the car from a stand still position.

At the completion of all three sections, students should better understand the engineers and their everyday goals that need to be addressed in order to complete their portion of a larger product. Each detail is specific to a certain aspect of the finished product. If one portion of the project does not meet the qualified standards then the production process is slowed. This leads to slower failure analysis simulations to show whether or not the finished product will meet the needs of the consumers. If the product fails the analysis, it must go back into the design phase and iterations are completed to correct the issues.

6. PLM Research Projects

The PLM Center is actively investigating two common-core projects with graduate students. The first project examines feature design changes and subsequent engineering time impacts as they cascade through a turbine component. The software package (e.g. NX) was used to create features in gas turbines and explore reductions in update times for patterning of turbulator tabs. Typically, there are thousands of turbulator tabs inside a serpentine channel located within a gas turbine blade to promote cooling, as shown in Figure 6 [14]. In a gas turbine, the inlet air is compressed in the compressors stage, mixed with (natural gas) fuel and ignited in the combustion chamber. Power is then harvested from the exhaust gas to generate electricity using a generator attached to the rotating shaft. A portion of the compressed air may be routed through the inside of the blades and surface holes to cool the blades. The turbulators are flow disruptors to help promote air mixture and convective heat transfer prior to exiting through the holes into the turbine chamber [14]. The serpentine surface turbulators can be created through the software using a patterning feature option. Any changes made to the drawings often require a significant amount of time which leads to the problem statement of how to decrease the change update time [15]. The software package offers several different patterning options which will be explored in detail for both linear and curved surfaces to identify which option is most suitable to implement the changes. Figure 7 shows an example of a test model created featuring a curved geometry surface with the patterned turbulators.

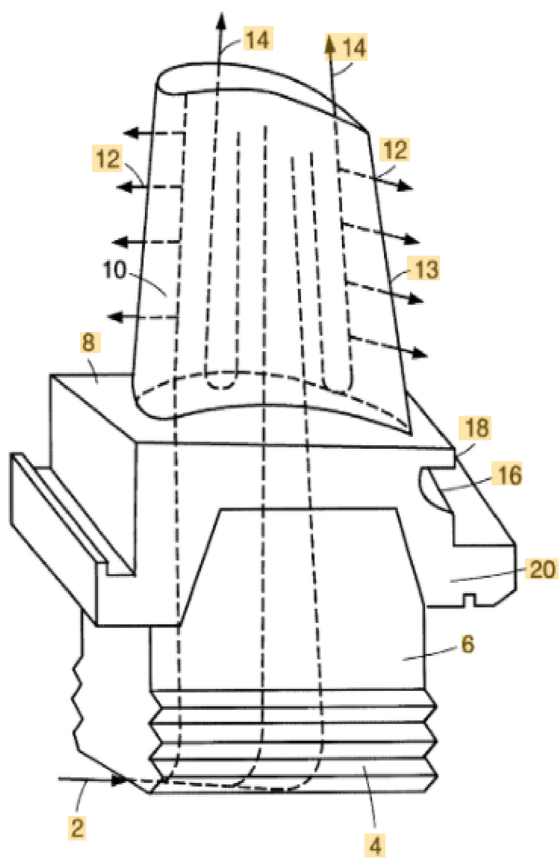

Figure 6: Serpentine channel inside of turbine blade [8]

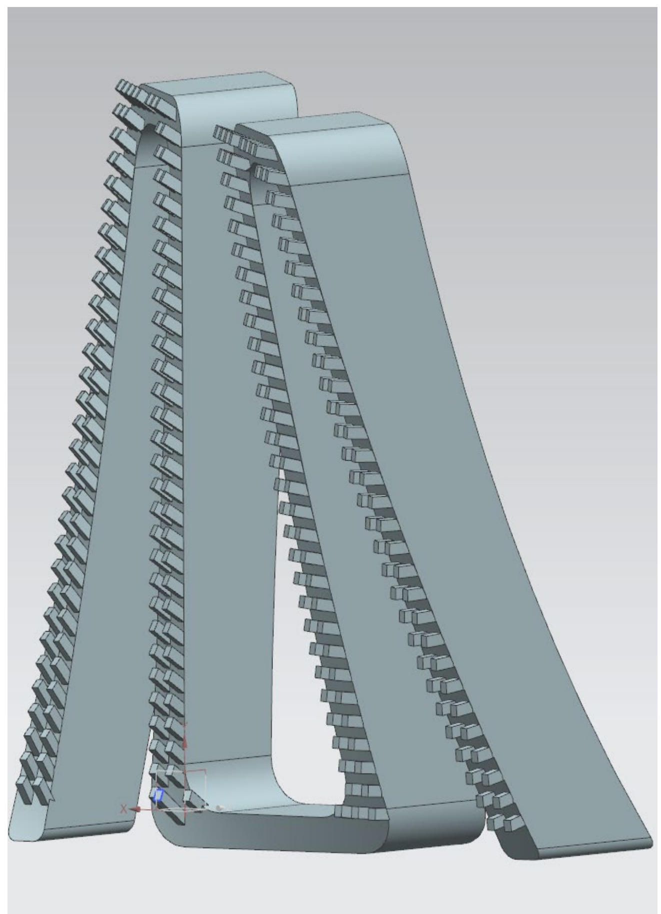

Figure 7: Curved geometry surface with turbulators patterned using CAD/CAE software for case study

The second research project investigates a digital twin for a large chiller plant with multiple campus building on the closed cooling loop. The heating, ventilation, and cooling (HVAC) process has four main components [13]: refrigerator loop (chiller), condensed water loop (cooling towers), chilled water loop, and building side loop as shown in Figure 8. The overall system features compressors, pumps, heat exchanges, fans, motors, valves, and a host of sensors. The SimCenter software package has now applied for the modeling and simulation of the thermodynamic, electro-mechanical, and fluid features to determine the system temperatures, pressures, and power ratings. After verification using operating plant data, the virtual twin will be executed simultaneously with the operating chiller plant for health monitoring and predictive maintenance [12].

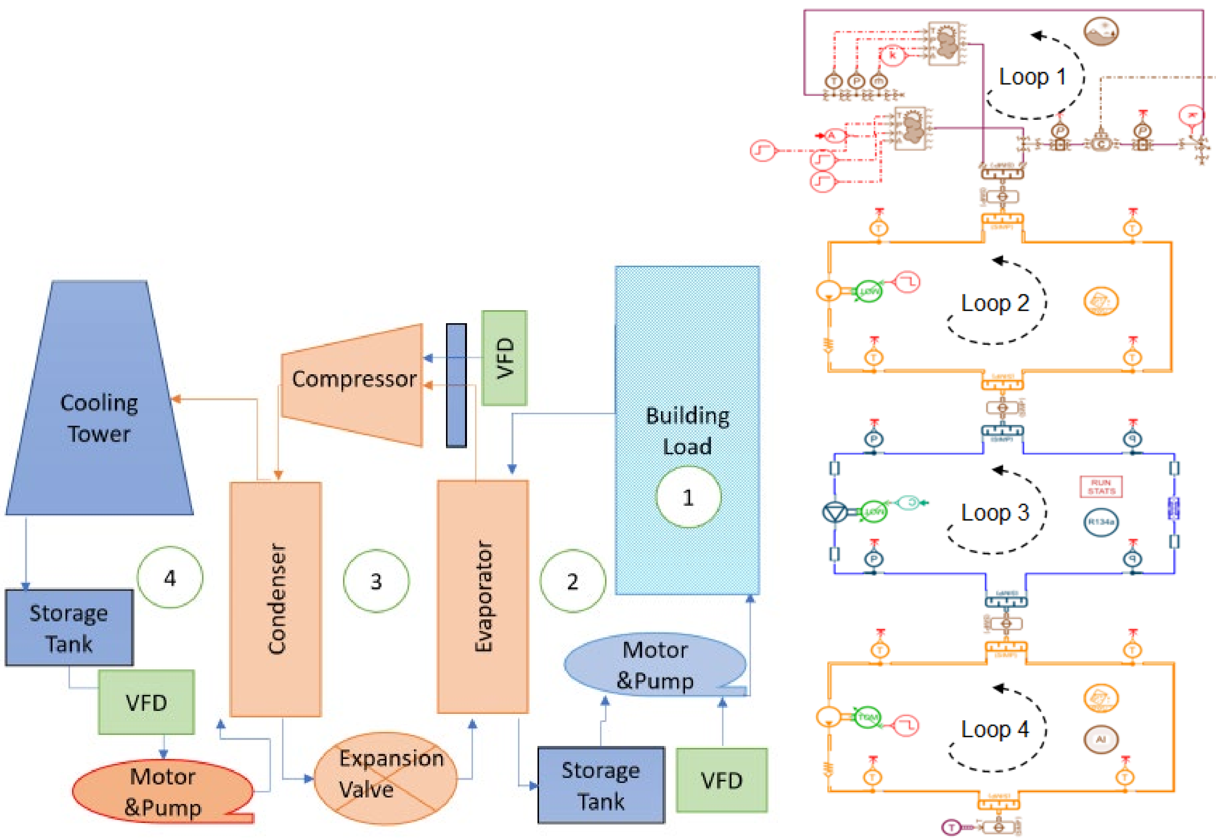

Figure 8: Digital twin schematic for a university chiller plant and campus buildings

The PLM Center serves students, staff, and faculty and regional companies with education and research opportunities. Product Lifecycle Management seeks to provide a universal platform where the diversifying software tools, data management and analytics, and business processes function as a single entity [2]. This will enable South Carolina companies to have access to PLM resources through the center for evaluations and to join fellow PLM practitioners. Additionally, these businesses will be able to obtain a visualization of the strength and advantages from PLM packages. PLM is an emerging industry standard with culture change in companies [10]. The users of PLM will be prepared for this paradigm shift and thrive in a constantly evolving market.

7. Conclusion

To remain competitive in the global business world, companies must embrace the digital design and production methods that are centered around Product Lifecycle Management system. PLM encompasses both processes and tools as well as their critical role in today's industrial landscape. The PLM learning materials including fundamental concepts, digital product development and graphical/non-graphical concepts, establish a foundation for accompanying software packages. Overall, these computer tools can digitize tasks for future data retrieval, data mining, and accelerated design cycles. In this paper, the PLM basics and their integration a BSME curriculum have been discussed. The PLM Center offers students and industry technical staff a place to go to gain the knowledge necessary to help their company as virtual engineering becomes more prevalent. The assessment survey located in the Appendix is administered to seminars and workshop participants to evaluate effectiveness. Lifelong learning for engineers is critical and PLM workshops will help them in the 21st century.

Appendix

Survey for evaluating effectiveness of workshops or seminars presented concerning PLM topics
Note: "Likert Scale" indicates usage of the following responses:
1) Strongly disagree, 2) Disagree, 3) Neither agree nor disagree, 4) Agree, 5) Strongly agree

Question 1: The concepts in the workshop/seminar were interesting to me.
Likert Scale

Question 2: The workshop/seminar has motivated me to continue learning about PLM topic(s).
Likert Scale

Question 3: The workshop/seminar was well-organized and clearly explained the digital concepts.
Likert Scale

Question 4: The workshop/seminar clearly established the relevance of the topics to business and industry.
Likert Scale

Question 5: The knowledge gained in this workshop/seminar will positively impact my (future) academic studies and/or professional career.
Likert Scale

Question 6: Which of the following would have the greatest impact in making the workshop/seminar more effective?
Multi-select:

- Revise the content of the presentation
- Improve the presenter's delivery and/or communication skills
- Provide more examples, demonstrations, and/or walkthroughs of digital concepts
- Offer better access to PLM software and/or learning resources

Question 7: Would you recommend this workshop/seminar to a friend or colleague?
Yes/No

Question 8: Please record any suggestions or concerns you have about the workshop/seminar, the PLMC, or PLM tools and processes.
Free response

Question 9: What is your academic year?
Single select

- Freshman
- Sophomore
- Junior
- Senior
- Graduate student
- Non-degree seeking

Question 10: If degree seeking, what is your major?
Free response

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