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A Pedagogical Framework and Course Module for Building Awareness and Know-How Related to the Digital Thread and Smart Manufacturing Using STEP AP242

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Abstract

Traditional manufacturing and mechanical undergraduate courses fall short in addressing a growing industry need for more skilled and versatile engineers that can use digital technology to bridge the gap between design, manufacturing, inspection, and enterprise functions. International efforts to develop and implement the 3D Model Based Enterprise (MBE), Standard for the Exchange of Product Model Data (STEP), Industry 4.0, Artificial Intelligence (AI), and Smart Manufacturing (SM) are creating tools and strategies to modernize and transform companies that are looking for a competitive edge. Automotive, aerospace, and medical device manufacturers who invested in software, equipment, and people to streamline product development and manage digital data are seeing significant improvements in productivity and connectivity throughout the lifecycle. Although the current body of literature and commercialization of both hard and soft technologies in these areas continues to grow, more course content, cross-training, and examples are needed to support these initiatives and educate students effectively.

This paper describes a pedagogical framework and learning module for a Computer Aided Manufacturing course at the Oregon Institute of Technology for both BSME and BSMfgET majors. An overview of relevant terminology and concepts was supported by examples of how 3D models with Product Manufacturing Information (PMI) can be used to improve decision making, apply best practices, and automate processes. Lecture material, software demos, and setup/machining/measurement of sample parts using a CNC lathe, mill, and coordinate measuring machine were used to reinforce the value of having a digital thread to evaluate both the processes employed and the product's performance over the lifecycle. Assessment results showed that previous courses provided a solid foundation for adapting to and comprehending the importance of a more modern and digital approach to product engineering and lifecycle management. This project produced a framework and course content that strengthens and modernizes our programs and addresses shortcomings identified by our Industry Advisory Board.

Introduction

To successfully teach and implement Digital and Smart Manufacturing concepts, companies will need a more flexible and technology savvy workforce that is familiar with key areas of computerized product development including design, engineering, manufacturing, and metrology. Advances in 3D CAD/CAM/CAE software tools and programming interfaces are providing a more robust environment for Product Lifecycle and Data Management (PLM & PDM). Furthermore, efforts to improve international standards for product data representation and exchange (STEP) are producing tangible results both in productivity and profits.

More educational materials are needed for engineering and technology students in the areas mentioned above. They are needed to introduce students to the 3D Model-Based Enterprise, PLM/PDM, the digital thread, and STEP AP242, a hybrid standard incorporating Product Manufacturing and Inspection Information (PMI) in the 3D CAD file/model.

The background, methodology, and results of this work are presented in this paper along with an example of an aluminum cover plate designed in a 3D CAD program that supports STEP AP242, programmed using CAM software, fixtured/machined on a 3-Axis HAAS machining center, and measured on a Mitutoyo Coordinate Measuring Machine (CMM). The use of specific software and equipment available in-house demonstrates how the technology and standards need to be personalized to specific products and companies (aspects of this project are discussed below in the Methodology section). First, the foundational knowledge from taking courses in both the BSME and BSMfgET degree programs is presented in a framework that goes on to describe a CAM course module on digital and smart manufacturing. A description of the examples used with students and the results of the assessment are also discussed. In addition to teaching students about the product lifecycle in the context of a digital thread, it also explains diverse perspectives and roles engineers play in collaborative product development and appreciation for knowledge gained in prior courses like Machining, CAD/CAM, GD&T, and Computing.

Background

Building blocks for utilizing Product Manufacturing Information (PMI) and tolerance representations for Smart Manufacturing (SM) are showing up more and more in research projects/literature and industry/product/process specific applications. For example, rapid prototyping, composite structures, robotic assembly, augmented reality, and architecture for incorporating business functions that depend on information from applications and product engineering activities were found [1]. Developers of standards like International Organization for Standardization (ISO), American National Standards Institute (ANSI), the American Society of Mechanical Engineers (ASME), to mention a few, have worked for years to provide a consistent way to store and exchange data for industrial products throughout their lifecycle in a machine readable or computer-interpretable form [2]. How the product's design and manufacturing information is authored, exchanged, and processed will determine which companies will succeed in this era. The metaphor 'digital thread' has been recently invoked to picture the flow of information along the product lifecycle and across the supply network [3]. As A.B. Feeney explains in [4], "Manufacturing systems in this new era will have to get 'smart'. They need to be autonomous, self-aware, and self-correcting. In short, they should be able to function with as little human intervention as possible, while at the same time working harmoniously with human supervision and collaboration." A hierarchy from [4] to highlight the enablers of Smart Manufacturing and its' dependence on data management and accessibility is shown to the right:

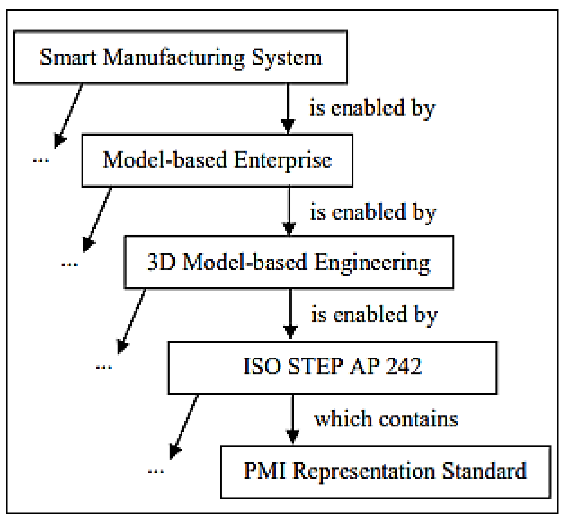

Figure 1: Hierarchical Enabler Diagram for Smart Manufacturing

The latest version of a more versatile and usable neutral format for storing, applying, and exchanging product data that will facilitate SM is the Standard for the Exchange of Product Model Data (STEP) and its associated Application Protocols (APs). STEP in general, and STEP

AP242 in particular will play an important role in the future of digital transformation and support the implementation of a 3D Model Based Enterprise (MBE) in companies around the world. The wide-reaching impact and potential this will have on Product Data and Lifecycle Management (PDM/PLM) are far-reaching and beyond the scope of this paper. However, certain aspects of STEP AP242 and how it is being used to improve product and process performance are important for current students studying Computer Aided Design and Manufacturing (CAD/CAM) and Computer Numerical Control (CNC) to understand. The course module described later in this paper focuses on using the 3D CAD model with PMI to develop sound strategies for Computer Aided Process Planning and Inspection (CAPP/CAI). The work done by the National Institute for Standards and Technology (NIST) at their MBE summit and with the latest update to their STEP File Analyzer and Viewer that was released in 2021 represents significant progress and a continuing investment of time and resources. Some conclusions from the summit were [4]:

- Model-based methods and tools are increasing manufacturing productivity, but challenges remain in composite structure manufacturing, additive manufacturing, and process data sharing. Model-based inspection and optical measurement are showing great potential.
- Light-weight visualization formats are making model-based engineering feasible for small and medium sized companies.
- Systems engineering is an increasingly important component of model-based enterprise.

The STEP File Analyzer and Viewer is "a software tool that analyzes and generates a spreadsheet or a set of CSV (comma-separated value) files from an ISO 10303 STEP file. The spreadsheets simplify inspecting information in the STEP file at an entity and attribute level. STEP files can also be checked for conformance to recommended practices for Product and Manufacturing Information (PMI) representation, PMI presentation, and validation properties. The STEP File Analyzer and Viewer also generates views of part geometry, graphical PMI annotations, tessellated part geometry, sketch geometry, supplemental geometry, datum targets, and finite element models [5]. A STEP file refers to a file that is typically exported by CAD (Computer-Aided Design) software in a neutral format that can subsequently be imported to other CAD/CAE/CAM/CAI tools for further work and analysis.

Model-based definition enables the digital thread, which promises to create the flow of information along the product lifecycle and across the supply network [4,5]. In addition to the 3D solid model, other metadata and design specifications such as geometric dimension and tolerance (GD&T) information, 3D annotation, surface finish, material specifications, welding symbols, and process notes are available in a STEP AP242 file, which enables collaboration, decision-making and the creation of other helpful file formats such as 3D-XML, STL, JT, and 3D-PDF which can be used for [6]:

- Visualization of engineering data
- Data exchange involving exact geometry
- Use in digital mock-up (DMU)
- Documentation and archiving
- Use of 3D information in PLM

"In a nutshell, STEP files are used to describe an ever-growing body of product information - like part geometry, tolerances, and assembly instructions—in a neutral format that can be exchanged between computer-aided systems, like computer-aided design (CAD) and computer-aided manufacturing, and integrate those designs into the broader enterprise systems [7]." A smart version of the 3D model for a part or assembly with PMI will lead to possibilities for artificial intelligence, computer aided process planning, data distribution, smart devices (IoT), and Industry 4.0 tools to be developed. It is critical that educators continue to build foundational knowledge, keep up with these topics, and incorporate them into classes using examples from industry as well as in-house CAD/CAM, CNC machines, and automated inspection equipment.

In [8], R. Lipman and J. McFarlane from NIST cover the use of PMI in AM. "Robust geometry and tolerance representations are needed in additive manufacturing for precise part specification and interoperability with downstream activities such as manufacturing, inspection, and long-term archiving. A disconnection exists between process-independent part geometry and tolerances, and process-dependent information requirements for additive manufacturing." The paper goes on to describe the details of how standards can improve AM, and their integration into the MBE paradigm. Since this topic is important to the U.S. defense industry, STEP files must be combined with other formats (STL, AMF, and 3MF) to address the unique geometry and tolerance demands of complex free form surfaces often needed for military applications. In another example [9], a system is described for using the 3D model with PMI to analyze the potential of automating the assembly process for products by extracting geometric and non-geometric data directly from the CAD system using the Application Programming Interface (API) and custom software developed in C#, C++, VB.Net, and VBA. Macros can be used early in the design process by non-experts to run evaluations and see if automated assembly is feasible.

These results can also be used in collaborative design, for adding to the digital thread, and in Design for Manufacturing / Assembly (DFM/DFA). The API tools now available in most commercial software are going to serve as a gateway to data collection, filtering, distribution, as well as opportunities to automate CAD/CAM/CAE with AI. The advances made at NIST with the translation of the STEP AP242 file to an Excel file that is both human and machine readable, combined with the viewer for the PMI enriched 3D CAD model are laying the groundwork for the digital transformation and smart manufacturing. The data is available. What is missing is understanding how it will be interpreted and applied to different stages of the product lifecycle for better decision making and the use of company specific best practices and know-how.

Methodology

A vibrant manufacturing industry demands a vibrant workforce with a wide scope of knowledge, expertise, and skills. [10] predicted that the US would need to fill around 3.5 million jobs in manufacturing while 2 million of these positions might remain unfilled due to the gap of skills. Today, the shortage of qualified workers occurred to around 80% of manufacturing enterprises [10]. In [11] the need for further education for students related to the digital and smart manufacturing is justified: "There is an emerging need to improve existing educational programs to enhance the learning experiences of students for an increase of retention rate." Wang's paper also describes the relationship between traditional engineering courses and computer-aided technologies to identify the gaps between current CAD/CAM teaching practices and the skill needs from manufacturing industries. Figure 2 shown below was taken from [11] and represents how current curriculums are broken (represented by chain links) and fall short in preparing students with the knowledge to implement and improve upon computer aided technologies and current systems that are already being used in industry.

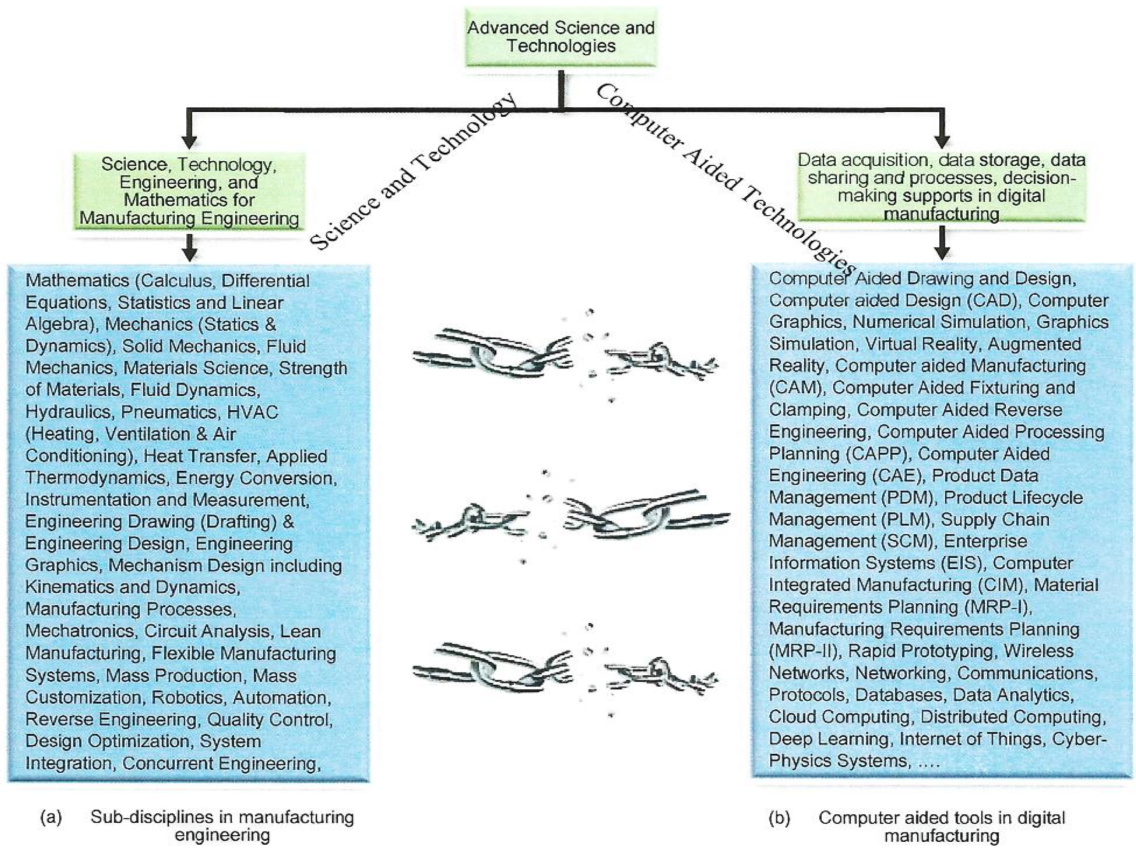

Figure 2: Traditional Engineering Courses -vs- Modern Digital and Computerized Courses / Concepts [11]

At the XYZ Institute of Technology, the required courses and corresponding curriculums do not cover information relating to the concepts of the 3D MBE, digital threads and other topics related to PMI data as it is embodied by STEP AP242 exchange format. The underlying concept of a digital thread is becoming more prominent in industry, but still vastly underused at the current time. Our objective is to outline a way to start implementing these core concepts into an existing course. In addition, this will help better connect other classes students have taken within the course catalog, such as 2D and 3D CAD, CNC programing, and GD&T courses (see Figure 3.)

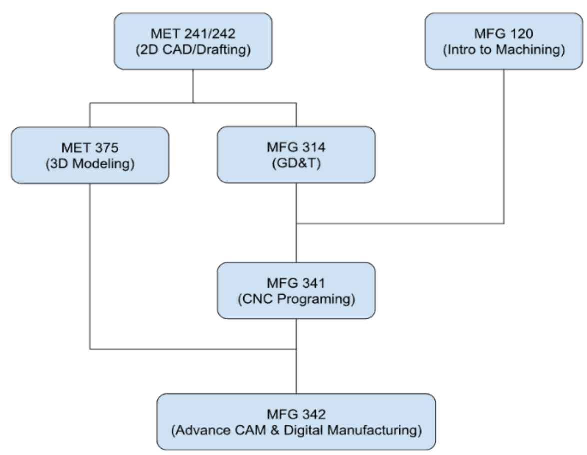

Figure 3: Mechanical & Manufacturing

Students at the XYZ Institute of Technology take two AutoCAD or 2D CAD classes, where they learn the fundamentals of CAD drawings and technical drawings. In addition, students take a solid modeling course which builds upon their 2D CAD knowledge, creating 3D models and assemblies. In parallel, students also take a GD&T class where they learn the fundamentals of GD&T and tolerances. Students also take an intro to machining course where they learn the fundamentals of machining and manufacturing parts. Manufacturing students and some Mechanical students also take a CNC programming course, where they begin to learn the fundamentals of programming and running CNC machines. A key goal/objective of implementing a focus on the larger product life cycle and manufacturing life cycle using STEP AP242 files and model-based definitions is to help tie these concepts from multiple courses together while students are learning and building these individual skills. The pedagogical framework in Figure 4 below shows how knowledge from current courses can be leveraged and referenced to increase awareness and know-how related to the use of digital technology.

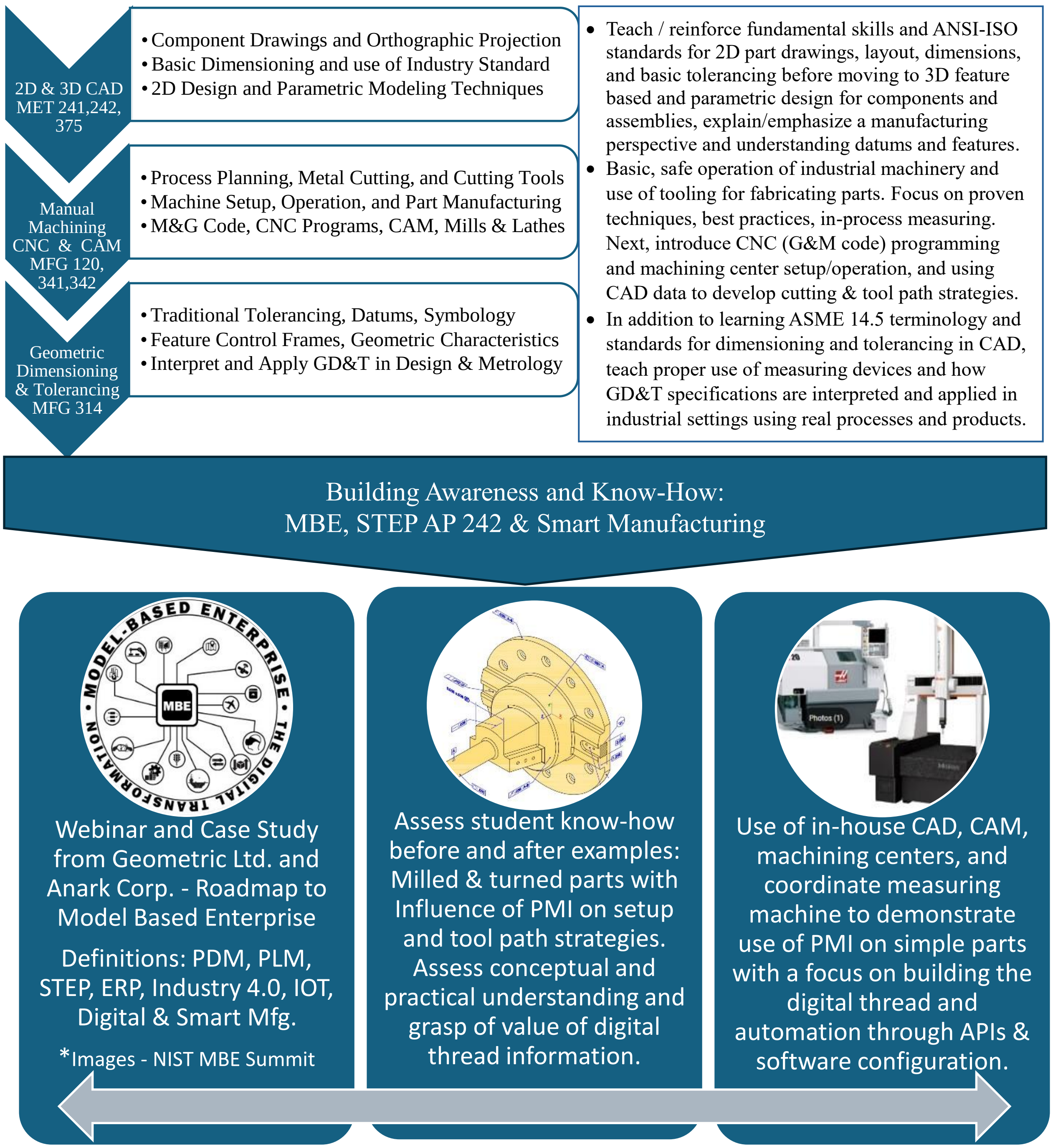

Figure 4: Pedagogical Framework: Prior Learning Used to Develop Digital Transformation Perspectives

Examples of Teaching Materials:

Creating a single or master file with all the relevant product and manufacturing information allows for better interchangeability but also streamlines processes down the road. Our concept is for a "Digital Assistant" that utilizes the data from a STEP AP242 built into either CAD, CAM, CAI, or other software's APIs, allowing the user to have the relevant information for their needs. In addition, this form of data is likely the next step towards more automated or AI processes. One example of this would be relevant PMI data is now able to be relayed to CAM processes. This form of automation is already apparent with CAI software, with the PMI data from a STEP AP242 being leveraged by CAI software to streamline the programing process of CMMs. The benefits from STEP AP242 when it comes to CAI software have already been shown to provide massive benefits and time savings, with hours of programing time being saved [12]. For companies to fully utilize these processes in the future, current Manufacturing and Mechanical Engineering students must learn and understand how these file formats and data can help streamline and innovate the manufacturing industry.

A short quiz was given to MFG 341 students after learning about manual g-code programing and CAM programing. Two questions asked students how simple GD&T features would impact how they might program and machine a part. The first example were two diameters on a turned part which needed to be concentric to each other within .002 of an inch, as seen in Figure 5 below. Students were then asked to pick all applicable answers to how the part might be manufactured to help meet the concentricity requirements; a - use the first 2.000in diameter machined as a reference for a second diameter, b - use the same tool and machine both diameters, c- machine both 2.000in diameters in the same setup, d - does not matter because diameters are on the same center axis, or e - all of the above. Answers a and c would be correct, as the concentricity callout controls where the center axis of each diameter is relative to each other, not how the diameters of each feature turned out as answer b would suggest. On these questions, the average score was 1.6/4 points, with many students struggling to identify the difference between controlling the axis of the features versus the diameters.

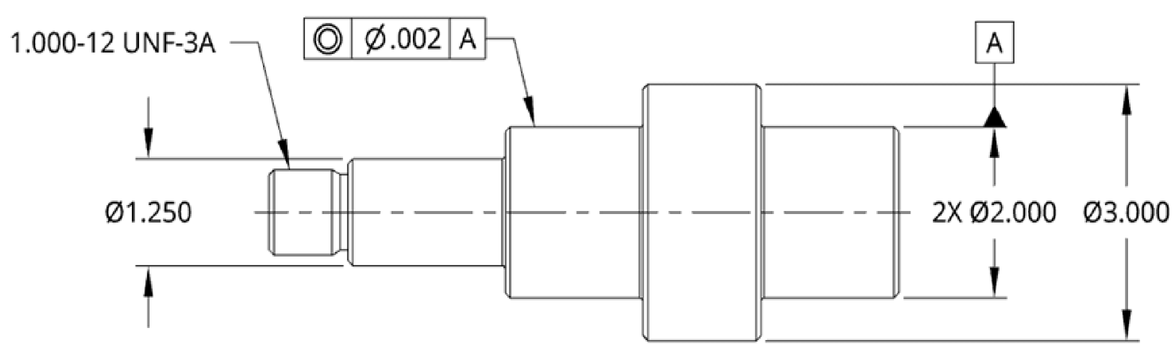

Figure 5: Quiz GD&T Question 1

This shortcoming in the student's understanding of how GD&T might affect the physical manufacturing process allows for the introduction of a tool which utilizes model-based definitions and the STEP AP242 protocol. This consists of a CAM digital assistant reading the

GD&T data from an imported STEP AP242 part, then helping the user or student understand how to interpret the GD&T data alongside recommended strategies to machine the part. While a tool like this would not be needed for an experienced machinist or programmer, it is a helpful learning aid for students just starting to move from theoretical GD&T tolerances to machining a physical part that meets those specifications. In addition, it is a hands-on way of giving students opportunities to utilize tools which can be produced from the STEP AP242 protocol. Figure 6 below shows how the tool can provide relevant information to the user based on an input from a STEP AP242 file, in this case being the part showcased in Figure 5.

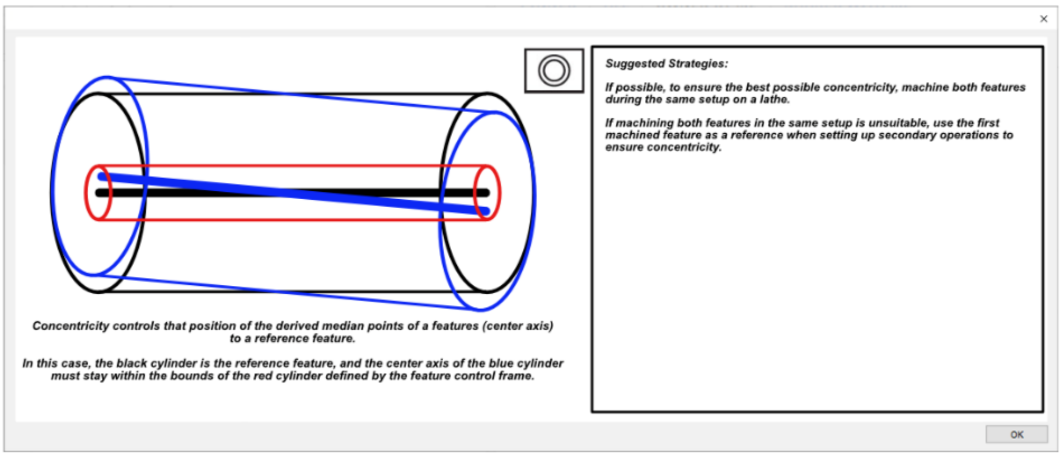

Figure 6: Example of the "Digital Assistant" for the Part Shown in Figure 5

The second example part that students were asked about in the quiz is shown below in Figure 7. In this case, the digital assistant provides information related to different ways to best machine this part. For this example, the part has a flatness tolerance across the top surface and is thin relative to width. From this information, the digital assistant might suggest using a large face mill to limit or eliminate the need for stepovers, helping in achieving a flatter surface. In addition, the assistant can provide information about fixturing and other factors, where in this case, a lower clamping pressure will be desired, or alternative fixturing solutions such as vacuum, and as a result the cutting force of the toolpath may need to be decreased. In addition, the digital assistant can take in other information, such as a tool library for a machine, where of the length of this part were to be much larger than the largest face mill, alternative strategies such as using a small tool with shallow stopovers to eliminate tram error in the machine might be utilized instead.

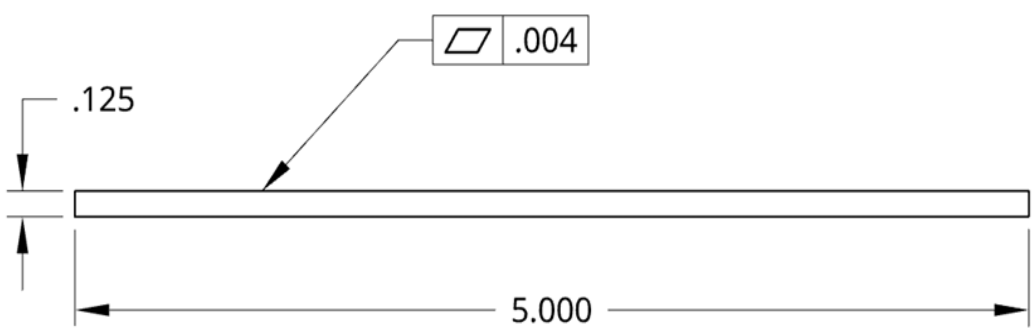

Figure 7: Quiz GD&T Question 2

Implementation:

The goal is to implement these concepts of PMI and model-based definitions, along with how to translate that information into real life through a project in our MFG 342 course. This project builds on an existing project where students program and machine a cover plate on a vertical machining center, which includes several setups and features such as an O-ring groove. Students are given a STEP AP242 file of a sample cover plate with all the relevant PMI data (shown in Figure 8).

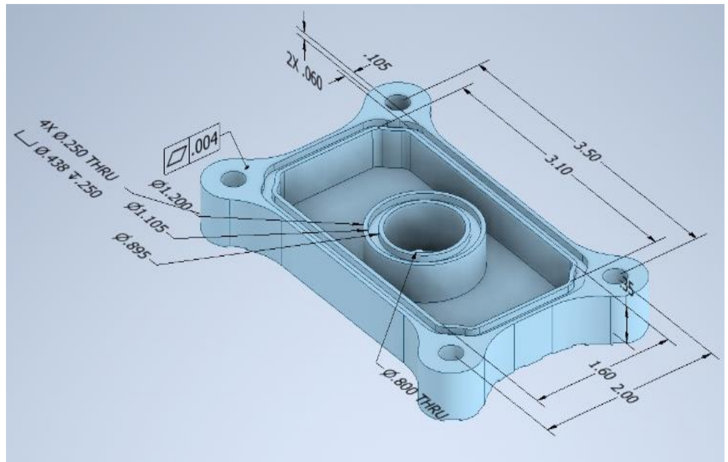

Figure 8: Provided STEP AP242 Cover Plate Example Part

As seen in Figure 8 above, there is a flatness feature on the sealing face of the cover plate. Through this project, students interact with the STEP AP242 file, along with learning how to translate the specs and callouts to the physical part. In this case, a simple flatness spec is provided, so students must decide on their strategy to machine it. Students can utilize the "Digital Assistant" to better understand and interpret the GD&T features along with suggest strategies for programing and machining. For example, how a large face mill can provide excellent flatness in a single pass but can struggle with parallelism or flatness with multiple step overs. This is where other strategies could be used such as shallow stepovers with a smaller tool to improve parallelism and flatness. Figure 9 below shows the "Digital Assistant" suggestions and analysis for this part. Students then get to measure their parts on a CMM, where they can see if they were able to achieve the desired flatness tolerance or not along with gaining a better understanding on how to measure the feature, in this case flatness. In addition to interpreting the GD&T data, the "Digital Assistant" can also provide secondary information such as fixturing suggestions or concerns.

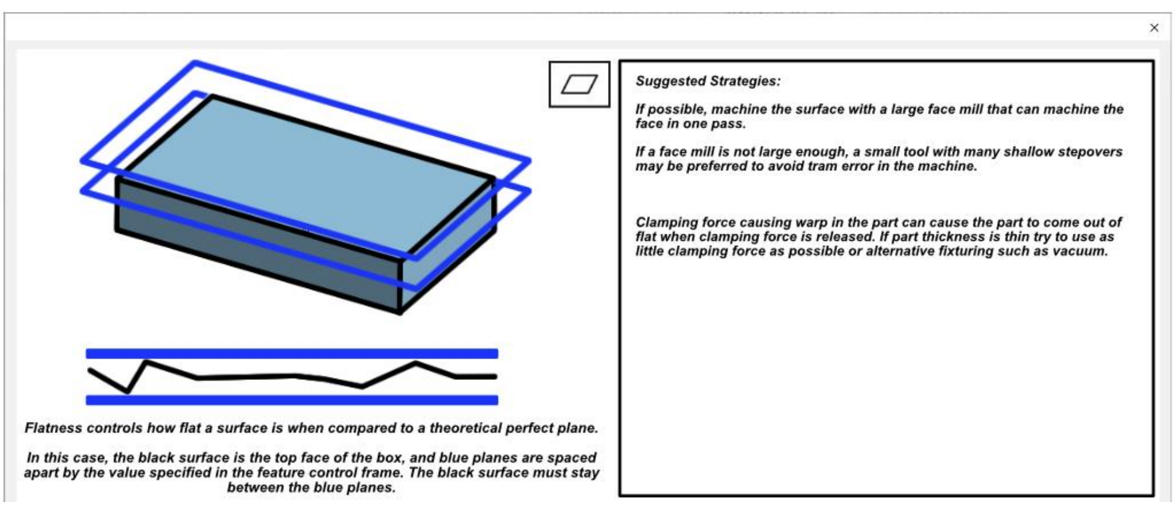

Figure 9: Example of the "Digital Assistant" of Flatness for Cover Plate Part

Case Study:

A case study was performed comparing knowledge and performance of students before and after implementing teaching material outlined earlier in this paper. Students received the same quiz at the beginning and end of the term, to both gauge their initial and background knowledge, while providing a direct comparison in the student's growth. This assessment focused on understanding of digital thread and smart manufacturing concepts along with GD&T implementations with the manufacturing process. These GD&T examples were outlined under the "Examples of Teaching Materials" section.

After students participated in the course which covered the topics outlined through this paper including smart manufacturing and manufacturing applied GD&T concepts, a significant increase in understanding of concepts and applied learning through projects was evident. An average quiz score of 81.43% at the end of the term over the initial beginning of term quiz with an average score of 45.45%. This data breakdown can be seen in the bar graph shown below in Figure 10. In addition, a farther breakdown of the data shows and large increase in student understanding of GD&T concepts and how they impact manufacturing processes and strategies.

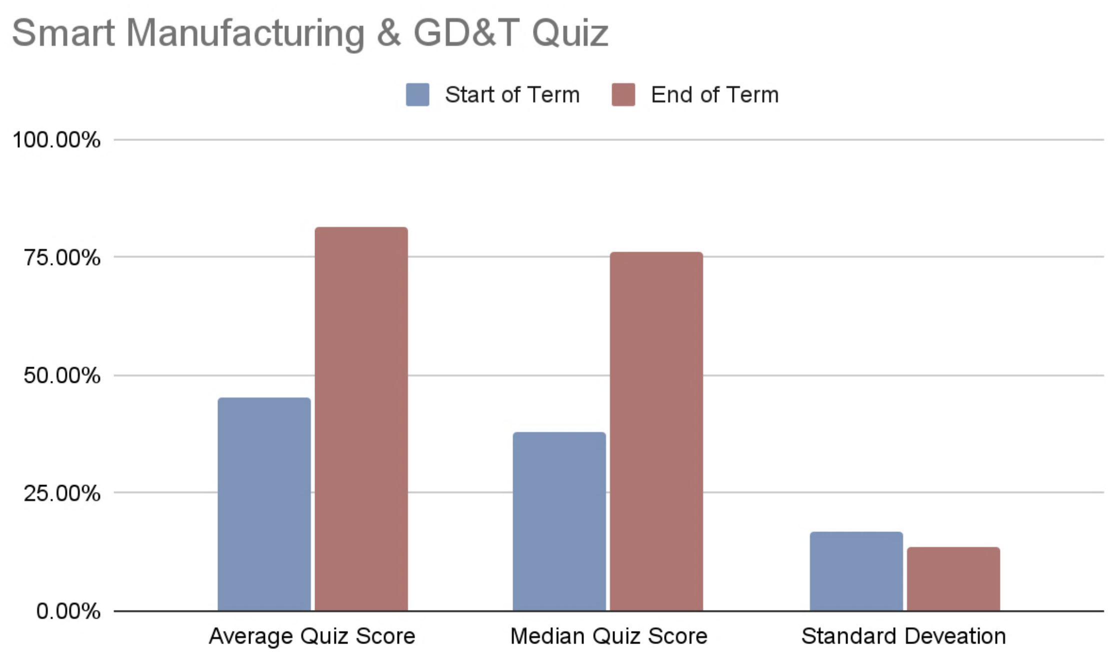

Figure 10: Bar graph showing before & after results from student evaluation

Overall, student understanding of Smart Manufacturing and GD&T concepts improved from the exposure and integration of these concepts into their cover plate project as outlined in the "Implementation" section of this paper. While students who took this course are not experts in any of these topics or concepts, they have a greater understanding than they would otherwise have, providing them with opportunities to bring these skills and knowledge into industry where it makes them more marketable, fills a gap in current company capabilities in these areas, and can be implemented and utilized as the technology continues to mature and gain momentum.

Discussion and Conclusions:

The STEP standard and application protocols are a work in progress. It will take many years to reach its potential for impacting manufacturing as it is envisioned. The advance of machine-readable representations in future editions of AP 242 will be key for automating using custom API programs that can serve as the gateway to data in CAD/CAE/CAM databases. Some of the biggest effects of STEP AP242 PMI will be in increased productivity by down-stream applications including prototyping, cost-analysis, computer aided manufacturing, process planning and inspection.

Currently there is a lack of knowledge around the concepts of model-based definitions and 3D PMI data in current engineering graduates. Our goal was to help provide our graduates with a better understanding of how these new technologies can be utilized as popularity and wider adoption of these tools continues to grow. Through the implementation of both lecture and hands-on experience, with the use of STEP AP242 files in our MFG 342 projects, students have gained a better understanding if these concepts and how protocols such as STEP AP242 can be utilized. In addition, focus has also been put on providing students with a better understanding of how GD&T relates to physical parts, machining, and inspection through these discussions, hands-on projects, and quizzes.

Continued implementation of these concepts and projects within our MFG 342 course will provide our graduates with future focused education within the engineering field. Further development of the "Digital Assistant" will aid in the teaching process, with implementation into CAM systems APIs, providing students with more specific, real-time information and feedback. In addition, implementing the use of existing systems, such as Mitutoyo's STEP AP242 support for them CMMs, will help better student's understanding. All of these items and concepts play a vital role in producing high level engineering graduates that will continue to be at the forefront of technology and engineering disciplines throughout their careers.

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