Method to Accelerate Student Proficiency in CSWP/CSWPA Solidworks Certification Exams and Fusee Mechanism Profile Analysis

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Abstract

Students in the University of Idaho's *Solid Modeling, Simulation and Manufacturing Capstone* (ME 490) course utilize Solidworks, one of the most widely used 3D CAD software in industry, to take eight certification exams to demonstrate competency in the program. This course has seen an increase in required instructional material, so this thesis presents a pedagogical method of introducing classroom material for the purpose of maintaining student pass rates with reduced instructional time. Exam scores and pass rates for CSWP Segments 1-3 and CSWPA Drawing Tools, Weldments, and Sheet Metal exams were analyzed between 2015 and 2019 to establish a target that needed to be maintained. During this period, instruction consisted of a wide range of tutorials. A new system was introduced between 2020 and 2021 that involved inquiry questions but fewer tutorials. The footprint of instruction dedicated to these topics was cut in half. However. when exam scores and pass rates were analyzed for Spring 2021 and Fall 2021, exam scores were maintained. This innovation created space in ME 490 for advanced topics in surfacing and special preparation for the CSWE exam. This new emphasis greatly expanded personal confidence in student CAD skills and heightened their interest in design for manufacturing.

Additionally, an analysis of a fusee mechanism is included to show how Solidworks can be used as a design tool and to determine the correct profile for the shape of a fusee to aid horologists and community clock makers in designing their clocks. Three mathematical solutions from the literature were analyzed and transformed for comparison. The Preisendorfer was selected as a baseline and all solutions were plotted along the length of the fusee. The greatest deviations in the forward marching solutions occurred at the smallest end of the fusee. The greatest deviations in the backward marching solutions occurred in regions where the slope of the fusee was greatest at the largest end of the fusee. The Preisendorfer solution is recommended for use by horologists as a starting point for a successful fusee manufacturing plan.

Acknowledgements

Enough thanks cannot be given to Dr. Edwin Odom for his tutelage and patience in this endeavor. Without him, I would not have developed an attitude of learning or have as much confidence attempting daunting challenges. His motto of, "see one, do one, teach one" has become one of my life philosophies that I hope to model for the rest of my days. Edwin has left fingerprints in my life that are far reaching and well defined. From day one, Edwin challenged me to push my boundaries and while quietly laying the foundational bricks to aid my success. I am fortunate to see how his years of experience and understanding have shaped his teaching style into a holistic worldview of learning that pushes beyond the walls of the school. Edwin, I wish you the absolute best in retirement and I want to thank you dearly for the life you have spoken into me and for the role model you have become. I will cherish the memories.

To Ian Glasgow, you have changed my perception of what friendship can be. You inspire me every day with your tenacity and your attitude of excellence. Our discussions and arguments have sharpened us both and made us better engineers and better people. Your jokes have kept me going when life seemed overwhelming, even if they're just as terrible as you look. Thank you for your complete support throughout our shared college experience. Seriously, thank you. I can't wait to run a marathon with you, even though I know you'll always be sprinting ahead. I wish you happiness and success in all your endeavors.

To Dr. Steve Beyerlein, Dr. Joel Perry, and Dr. Eric Wolbrecht, thank you for your time, patience, and energy in my development as an engineer. Getting the privilege to work with each of you has been an honor and I will take what I've learned from you and apply it to my career and to my practice. I hope to eventually teach others and if I'm able to achieve just a fraction of the ability that you each possess, I will consider myself successful.

Dedication

To Dad, Mom, and Laura. I cannot express the love I have for all of you. I value you more than gold and owe you more than I will ever be able to give. I can't wait to raise my future kids and share with them what you have given to me. If I had a penny for all the times that I have loved you, missed you, cried with you, called you on the phone, or laughed with you these past two years, it would be enough for dad to consider actually retiring. You have spoken into my life and shaped me into a man who is confident and resourceful. I love you.

To Caleb, my best friend, I don't think I'll ever be able to fully realize how lucky I am to have met you and grown with you over my life. I deeply cherish the times we get to hang out, joke about life, talk about the meaning of life far into the morning, and deepen a friendship that already has a lifetime of growth. If our friendship was a person, it could drink now, and I think that is literally the best possible measure for how good a friendship could be. It's an understatement when I say that I'm excited for where the future takes us both. I love you buddy and I can't wait for the next eighty years of terrible jokes and raucous laughter.

To "The Boys," Ian, Pugel, Danny, and Kris, I can't thank you enough for the memories we have shared. I love getting to hang out with a group of guys who are wicked smart, kind, responsible, and **so damn funny.** Here's to the next ten years and to all the ones after.

To JJ, thank you for being a valued friend and mentor in my life. You have given me opportunity after opportunity to experience new things and have invited me into your life. I can't wait to see you and Emily become a fantastic set of parents and raise your children to be successful and kind. Never stop exploring new beers, especially at the Pour Company! May the Bavik never stop flowing!

And lastly to Janelle Oberbillig, Brittany Brown, Katie Matsuura, and Elyse Thorpe, I thank you for the energy you have poured into my life. Each of you have been fundamental to my understanding of the world and have been present for critical moments in my development. You have left imprints of morality, excellence, and creativity in my life that I hope to share with the people I interact with every day. I wish you all the best in your teaching careers and I hope that you continue to inspire the students you work with every day.

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Chapter 1: Introduction

Engineering in industry and throughout history has been driven by education. From the ancient era to today, engineers must study practices, tools, and theory to create a foundational basis of understanding that can then be used to design and build the ideas of the future. Universities lie at the heart of this learning and across the world, engineers begin their learning at the collegiate level with basic formulas, tools, and projects. One aspect of learning that mechanical engineers must complete, so they can meet the demands of industry, is how to effectively use a 3D CAD software. 3D CAD offers the mechanical engineer the ability to create virtual models and test the models for fit and function without enduring the cost of creating physical models. This ability is vital to modern students and so the students at the University of Idaho are required to take a skills course to teach them the basics of one of the most common 3D CAD software on the market: Solidworks. The University of Idaho, after seeing success in the basic course, has decided to create an advanced course to help students explore further and hone their skills to an expert level. As the University of Idaho continues to add to the advanced curriculum, material must be created and evaluated to determine if the material can successfully maintain student scores while expert level content is added.

This thesis will attempt to analyze new material additions to the *Solid Modeling, Simulation and Manufacturing Capstone* course based on student points per minute and pass rate for the CSWP, CSWPA Sheet Metal, Drawing Tools, and Weldments exams. This analysis will include examples of new material and how it is beneficial as well as any outside material that was evaluated to be a positive addition to the curriculum.

This thesis will also attempt to demonstrate how Solidworks can be used as a research and design tool through the case study analysis of a fusee mechanism for a mechanical clock designed by the master clockmaker, W. R. Smith. The analysis will compare derivations for the fusee profile with the purpose that the final profile can be imported into Solidworks to be modeled and then put into the clock for a gear train analysis as well as be manufactured with a CNC.

Chapter 2: Literature Review

Solidworks

Solidworks is a 3D Computer Aided Design (CAD) software package that was initially released in 1995 as a product to fill the business market space between large expensive 3D CAD packages and low-cost, limited CAD packages. The goal of the software was to provide an easy to learn and use platform for engineers and designers to build 3D models and create products. The Solidworks company was acquired by Dassault Systèmes in 1997 and has grown to be one of the most widely used CAD programs in the world with over 3 million users worldwide. Users have the ability to take certification exams to show their knowledge of both the general features and of the more specific packages within the software.

The University of Idaho has been teaching students Solidworks for over a decade and has introduced an advanced Solidworks course entitled *Solid Modeling, Simulation and Manufacturing Capstone* with the purpose of preparing students to take the certification exams released by Dassault Systèmes. During the progression of the course, the mechanical engineering department decided to add more content exams to the scope of the course and sought out resource books like *Certified SOLIDWORKS Professional Advanced Preparation Material*, by the Certified Solidworks Instructor (CSWI) Paul Tran [1]. The book by Tran offered several guided problems for readers that covered the five Certified Solidworks Professional Advanced (CSWPA) exams: Drawing Tools, Surfacing, Mold Tools, Sheet Metal, and Weldments. These chapters introduce the reader to the tools used in the section, provide example parts for the reader to work on in parallel to reading the book, and serve as a guide on how to apply the tools to the provided examples.

Additional resource books were used by the university including *Certified SOLIDWORKS Expert Preparation Materials* and *SOLIDWORKS 2018 Advanced Techniques* by Tran [2]. These resources were used as supplementary material to help build more understanding of the surfacing exam and for providing workbook examples for the Certified Solidworks Expert (CSWE) exam.

Other materials were used in the course including sample exams that were released by Dassault Systèmes. There is a sample exam for each CSWP level certification exam offered by Solidworks. These materials were used in the course because of their inherent relationship to the exam. The sample exams can be obtained through the Solidworks website as well as a list of topics that the examinee will be tested over. These resources, combined with problems discovered in previous semesters, prompted the suggestion that the university develop a set of material that could replace or enhance the current curriculum for the purpose of increasing student pass rates and decreasing the reliance on purchasing new example problems year to year.

Strutt Epicyclic Train Clock

Plans for the Strutt Epicyclic Train Clock were purchased from the master clockmaker W.R. Smith that detail his manufacturing process and important notes on the workings of the clock. In the plans, Smith uses a template for a mechanism called a fusee, which converts the linear torque versus rotational behavior of a spiral spring into the linear curve needed for a clock. This profile provided by Smith was a sketch included in the plans and though correct, it is not in a form useful to CNC machining. Therefore, an analysis was performed to calculate the slope of the fusee.

The Science of Clocks and Watches by A.L. Rawlins provides a basic work on the science of horology and covers a wide variety of topics [3]. Examples include pendulum and escapement mechanisms, energy storage and impulses within clocks, and most important to this analysis, the equation of a fusee. A fusee is a cone-shaped pully that normalizes the force coming from a mainspring on a clock so that the clock can keep a consistent time. Rawlins derives a formula for the equation of the fusee in the third edition of his book but is believed to be incorrect by F. Powell. Powell offers a differing solution that includes an additional change in radius term in an article published in the Horological Journal in August of 1975. In November of the same year, R.W. Preisendorfer published a response to Powell's article that also believed Rawlins was incorrect but made an additional claim that Powell was incorrect as well. Preisendorfer published his derivation of the fusee profile in the Horological Journal in 1977 with the inclusion of one more term into the equation, the pitch term. All three authors set up the problem differently, but none solved all three formulations in a form to allow for comparison.

A publication by Swift that details the method of determining the spring constant of a spiral spring was also used [4]. The method requires taking radius and angle measurements of an unwound spring to find the center of the spring and to determine the equation that defines the shape of the spring. Once the shape is determined, material constants can be taken into consideration and a force versus angular displacement chart can be produced, where the linear slope in the middle of the chart can be found to be the average spring constant for the spring.

Chapter 3: Solidworks Pedagogy

Introduction

The widespread use of Computer Aided Design (CAD) across mechanical engineering has changed the nature of the industry in the past half century. The role of the drafter has been incorporated into the main responsibilities of the mechanical engineer, requiring the knowledge of how to draw and define objects in 3D space. Solidworks, a 3D CAD software, has become one of the most widely used programs in the world for designing, changing, and communicating complex three dimensional products and machines. Students at the University of Idaho learn to use the software during their undergraduate studies and leave with an acceptable level of understanding of the program, based on the majority of students achieving their Certified Solidworks Associate certification, the CSWA [5]. The University also offers an advanced Solidworks course entitled *Solid Modeling, Simulation and Manufacturing Capstone* that prepares students to take seven Solidworks certification exams that are released and proctored by Dassault Systèmes, the company that sells Solidworks [6]. This course has been a relatively recent addition, so the university had been experiencing low exam scores and pass rates because of the unfamiliar material. As the course progresses, the mechanical engineering department wants to improve exam scores and pass rates with the unfamiliar exams and develop material that will aid student learning in the class.

This section covers the introduction of Solidworks learning material that was created by a certified Solidworks expert and analyzes the effects of the material based on exam scores. This chapter will be discussing the changes regarding CSWP Segments 1- 3 and the CSWPA Drawing Tools, Sheet Metal, and Weldments exams. The CSWPA Surfacing and CSWE exam materials are being separately evaluated by Ian Glasgow, CSWE-MD/S [7]. Each exam section will discuss a relevant example of a homework problem that was introduced and an analysis of exam scores from previous semesters. Anonymized student data and created instructional material can be found in the digital library referenced in the appendix.

Learning Environment

The IdeaWorks computer lab (Figure 1) is a room that was introduced in 2009 as a space to inspire and engage students to share their energy, ability, and creativity and to act as a collaborative environment between students, faculty, and student groups [8]. It features a computer setup that was designed to foster conversation within the students, enabling a free flow of discussion and peer-to-peer help with work. This lab was chosen to host the course because of its design philosophy and because of the desired nature of the course: to help students collaboratively develop an advanced degree of skill. Observations were made in the years teaching the course that the open nature of the lab helped students connect with each other and increased their overall understanding of the material being presented. In Fall 2020, the lab was upgraded with a large central TV screen to enable the instructor to better incorporate demonstrations in class and was a very well received addition.

Figure 1: University of Idaho IdeaWorks computer lab

Course Additions

In Spring of 2013, the mechanical engineering department introduced Solid Modeling, Simulation and Manufacturing Capstone as a student elective with the goal of exploring the certification exams offered by Dassault Systèmes [6]. The first semesters were intent on taking the first three sections of the Certified Solidworks Professional exam (CSWP). Later, four of the five Certified Solidworks Professional Advanced (CSWPA) exams were added. They include Drawing Tools, Sheet Metal, Weldments, and Surfacing. In Spring 2020, the Certified Solidworks Expert (CSWE) exam was added as an optional part of the curriculum. As exams were added to the course, the content for the class was required to be condensed to accommodate the new material. The content for the exams went from spanning more than a month in the first semesters of the class to sometimes only a single week of class time on a single subject in the later semesters. This provided a challenging problem for maintaining student scores as more content was added and less lecture time was devoted to teaching the same amount of material. This decision was made with the claim that student performance would drop in the sections with reduced instructional time and that the goal of the new material would be to minimize this drop while still maintaining pass rates.

Content and Homework Changes

As the scope of the course began to include the CSWPA exams, it was decided to utilize the preparatory book, *Certified SOLIDWORKS Professional Advanced Preparation Material*, by the Certified Solidworks Instructor (CSWI) Paul Tran to aid in learning the new material in the exams [1]. The book provided guided bookwork problems for all five of the CSWPA exams along with part files to work on and modify. The examples detailed the different tools and options associated with the relevant sections and how to complete problems like those seen on the exam. Unfortunately, problems on the CSWPA Mold Tools exam were much different than the example problems in the book and focused on different tools. This problem with the Mold Tools exam, combined with general issues with explanations for certain actions and methods on problems, caused the decision to move away from the book. The challenge to develop material specifically for improving the University of Idaho’s solid modeling program began. The process involved evaluating what skills and problems Dassault Systèmes had decided were necessary and reflective of real life, developing homework and example problems that covered the necessary skills, and lastly introducing the material in a way that would help students with the core understanding of the actions they were taking. As of Fall 2021, all sections of the book by Paul Tran have been removed from the curriculum. Examples like the one featured in the Drawing Tools section of the book (Figure 2), demonstrate that tools are demonstrated but are not explained. This can lead to gaps in understanding of why certain tools are used and how they can be used most effectively.

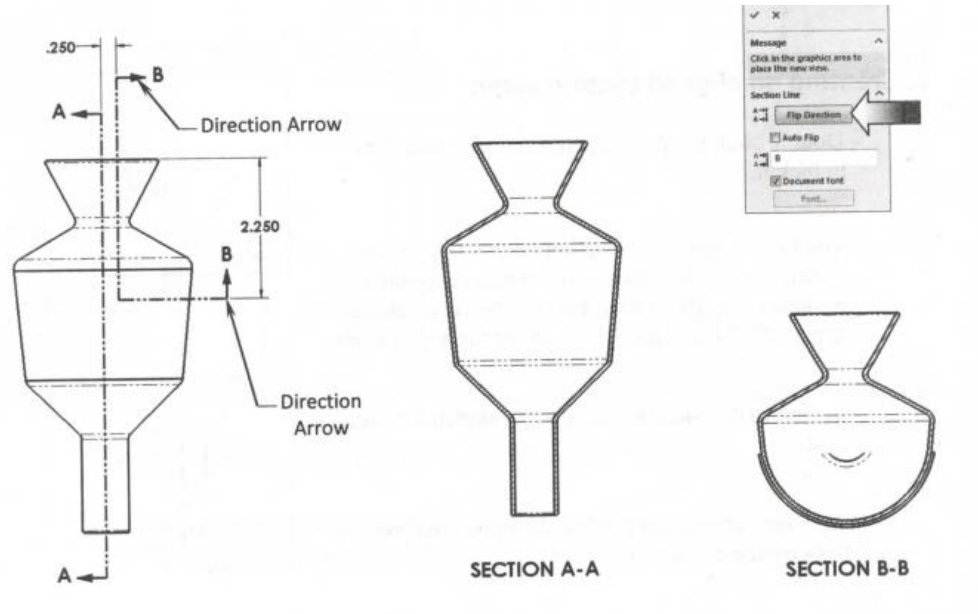


Figure 2: Drawing Tools aligned section view example by Paul Tran

Certification Exam Results

Data was recorded and analyzed for all students who utilized a University of Idaho Solidworks exam code, and the complete data set can be found in Appendix A. Data for certain semesters have been excluded from the graphs in this section based on the limited number (n < 5) of exam results from the semester, which is a result of non-enrolled students taking the exams or exams taken during a semester where the course was not being taught. One important factor to note is the number of failures may not be consistent due to retakes being included in each exam analysis.

CSWP Segment 1: Part Creation and Modification

The first segment of the CSWP is regarded among the students who have gone through the course and by the instructors to be the hardest of the three segments. It requires critical thinking skills to effectively create the parts on the exam within the time allotted and doesn't require any specialized tools or features. Content for this section was both created for and adopted into the curriculum based on the requirements of the exam.

While teaching the class, the parts released for the annual Solidworks Model Mania competition were discovered to be an excellent resource for this particular exam. The Model Mania competition is a yearly Solidworks skill competition held at the annual Solidworks conference and features a multiphase part with advanced features and complex geometry considerations. These parts offer a significant design challenge for the time period allotted and, due to their creation by Dassault

Systèmes, offer inherently similar challenges to the exam for this segment. Model Mania parts from 2006, 2009, 2010, and 2020 were selected as homework parts for students to complete on their own.

Figure 3: Model Mania 2010 phases 1 and 2

Figure 3 shows a complex part modeled in a Phase 1 drawing and then is changed in a critical way during Phase 2 that requires the user to use advanced critical thinking skills to plan for future design changes. Going from a mirrored section to one that is asymmetric represents an advanced challenge for the user within the timeframe allowed for the exam. When taught to use techniques like utilizing the rollback bar and using feature fillets versus sketch fillets, the design process is sped up, increasing the efficiency of the student. Advanced techniques like the one stated above are what distinguish using Model Mania parts from traditional parts.

Additional content has been developed to help the student learn specific modeling cases used in the exam. The measuring cup shown in Figure 4 below was created to demonstrate using nonstandard planes to aid in part creation. The edges of the measuring cup's handle are tangent to the surface of the cup itself, and a reference plane must be created beforehand to act as a boundary plane for the handle extrusion. This is paired with using the rib feature for the supporting rib on the bottom of the handle, to demonstrate the rib tool's efficiency in the modeling process compared to a traditional extrude.

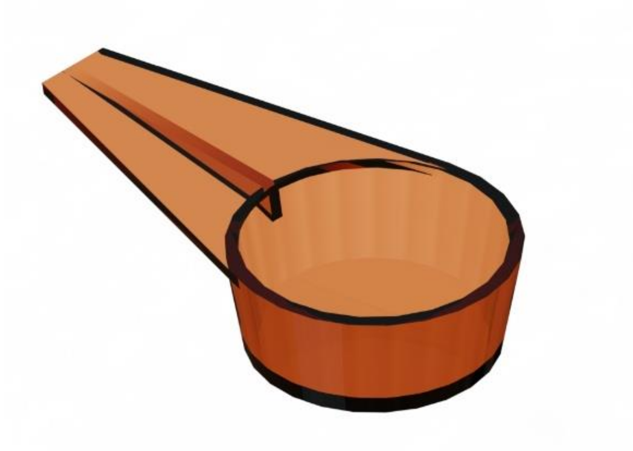


Figure 4: Measuring cup example

Exam results for this exam, shown in Figure 5, show that pass rates have remained relatively steady for this exam. While the number of students in each class fluctuated (indicated by number of passing attempts), the overall ratio of scores have steadied. The average pass rate across all semesters is 69.2% and 68.7% across the most recent five semesters. These pass rates are lower than the other segments and help confirm the belief that this is the hardest exam among the three CSWP segments. One reason this is believed to be a hard exam is because it tests the student's ability to critically think about feature order, sketch relations, and part modifications while in a testing environment.

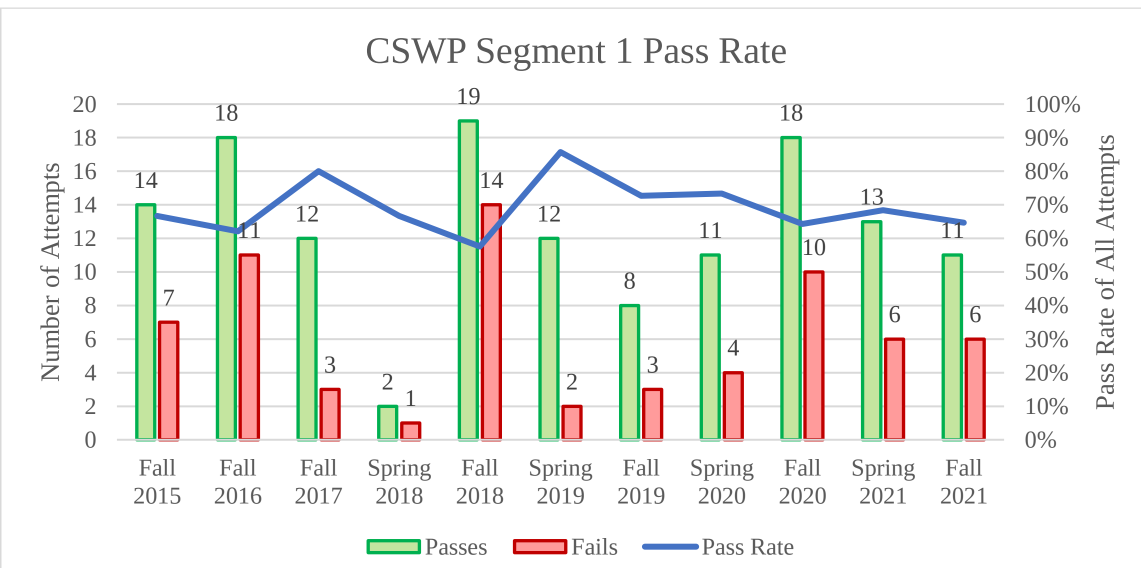


Figure 5: CSWP Segment 1 pass rate and number of pass/fail attempts

When evaluating the CSWP Segment 1 exam results from the past semesters of the class, it is important to factor in things like the average time it takes for students to finish the exam and the duration the material was taught for. Figure 6 shows the point distribution in each semester normalized for the duration of each exam time. This plot is an indicator of student performance and learning based on the need to recall information quickly and accurately during the time-critical exams. The CSWP Segment 1 results indicate there is a larger variance in student scores since the introduction of the new material. It is important to note that the classroom time for this exam has been reduced from four to five weeks, to one week because of the changes to include the CSWPA Surfacing and CSWE curriculums. Acknowledging this decrease in timeframe, the relatively consistent results indicate a positive effect from the newly introduced material and teaching style. The minimum points per minute (ppm) required to pass is 1.07ppm and is represented by the red line in Figure 6. One limitation to this line is the inclusion of exam scores in the data that did not finish the exam because of crashes in the testing client or because a student decided to quit or end the exam prematurely. Regardless of this limitation, it is believed that this line is a good indicator of student comprehension. One additional note to consider is the difference in the scores for this section of the CSWP versus the other two sections. This segment does not experience the drop in scores after Fall 2017 like the other two exams do but still sees a large number of failed attempts. It is hypothesized that this lack of drop is because of the difficulty of this exam and because it relies more on critical thinking instead of rote memorization of patterns in Solidworks.

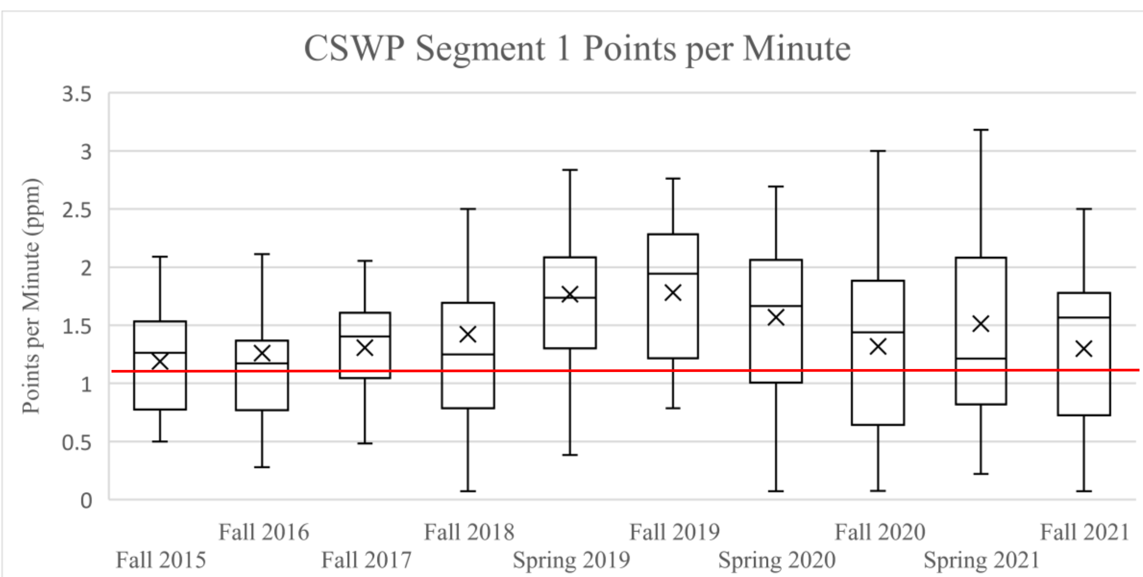


Figure 6: CSWP Segment 1 points per minute

Another important factor to consider is the effect of the Covid-19 pandemic. Across the entire world, the effect of Covid-19 can be seen through an increase in work from home lifestyles, issues with physical and mental health, and large impacts to student learning patterns and behavior [9]. The move to online learning led to feelings of boredom, anxiety, and frustration in students. Luckily, the data suggests that these problems were mostly mitigated and may not have had a large impact on student scores.

CSWP Segment 2: Configurations, Design Tables, and Feature Order

The second segment of the CSWP is considered to be a medium difficulty exam among students. It covers topics like feature configurations, modification of dimensions through design tables, and design tree manipulation. This exam offers multiple ways to solve problems because of the different ways to configure features. The specialized tools in this exam include creating design tables (a modifiable table that can create and control configurations through Microsoft Excel), the feature properties dialog box, and the modify configuration box. All homework and classwork content for this section was created and introduced into the curriculum based on the requirements of the exam and to give examples of real-life case scenarios where the tools can be used.

This segment of the CSWP is an easy segment to visualize because of the power that configurations offer. The pawn exercise shown in Figure 7 is a demonstration used in class where the major dimensions, features, and color of the pawn can be changed through an Excel table without ever having to create or edit the features for each configuration. Learning happens quickly with this kind of in-class activity because students can get an instant cause and effect relationship by editing dimensions and features.

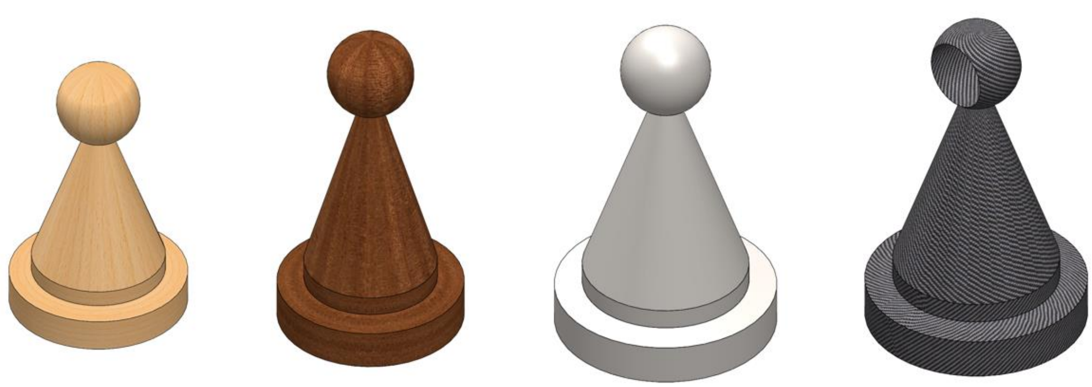


Figure 7: Pawn exercise

Another in-class example is the Castle Quiz. The Castle Quiz is designed to prepare students for editing feature order and for repairing broken relations. Figure 8 shows that students need to create a battlement on the turret of the wall while maintaining the wall curvature. This activity is designed to test a student's ability to recognize that utilizing the feature tree to edit previously created features can be an efficient and effective solution to adding overlapping geometry while also exposing students to editing or fixing broken relations after they change reference points.

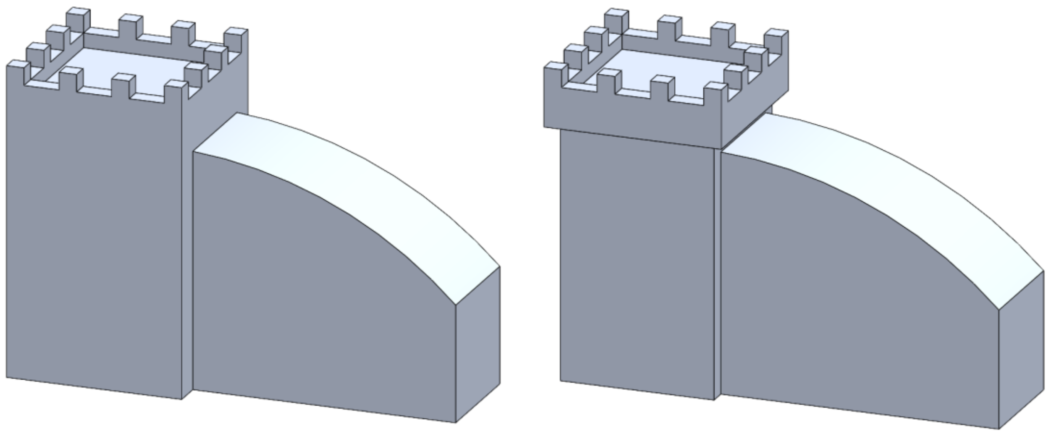


Figure 8: Castle quiz battlement modification

While this example is designed to be solved using the method stated above, it can be solved in several other ways and students are encouraged to explore other solutions. One learning outcome from this exercise is there are often many ways to get to a correct solution and there are almost always better solutions.

The CSWP Segment 2 exam results (Figure 9) from previous semesters show an interesting trend. Pass rates have fluctuated from 60-80% since 2018 with Spring 2020 being an outlier semester for pass rates. The average pass rate is 80.5% over all semesters and 78.9% across the most recent five semesters. If certain outlier data is excluded, the pass rate in Fall 2021 increases and establishes a positive trend after Fall 2019. The relatively consistent pass rate is a positive indicator that material additions are effectively replacing the older material.

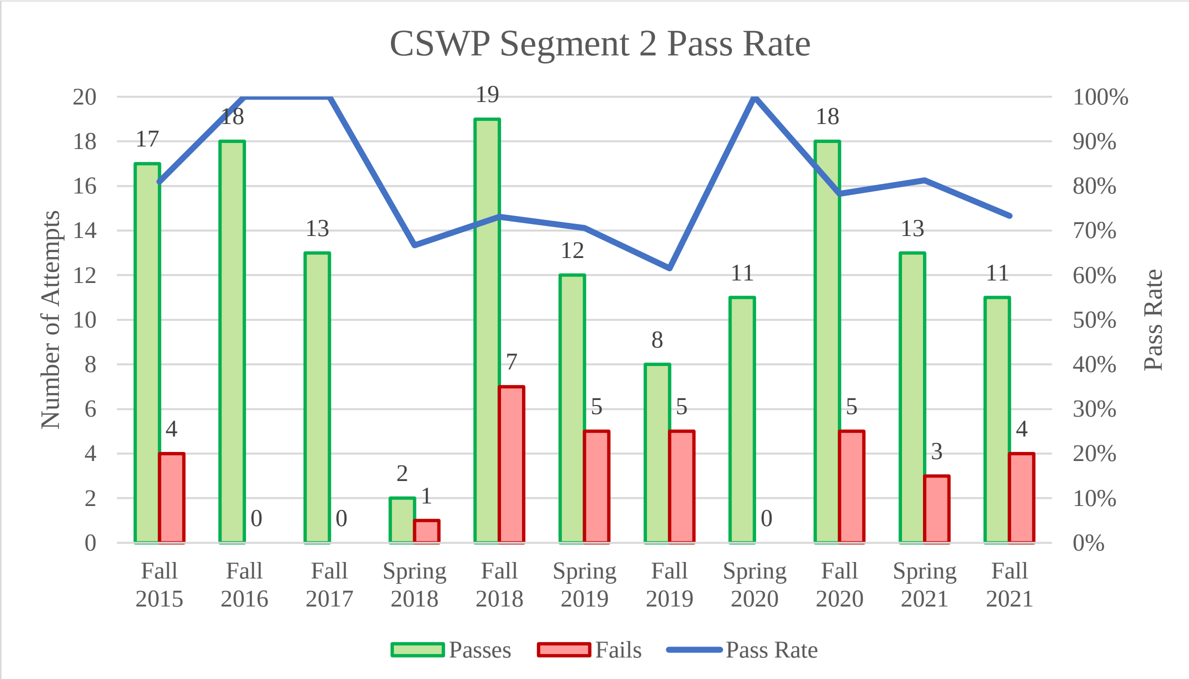


Figure 9: Segment 2 pass rate

Figure 10 shows a dramatic decrease in student ppm starting in Fall 2018, along with a general decrease in variation of student ppm in the later semesters. The drop in student score per minute correlates with the shift toward taking more exams per semester. Taking this shift into account explains the drop in student performance per minute and provides evidence for the claim that spending less time on instructional material for the exam in favor of other exams will cause a drop in student ppm. The introduction of new material into the curriculum seems to cause the decrease in variation of scores over the last three semesters relative to the previous four semesters while still maintaining pass rates. The minimum ppm required for this exam is 1.54 ppm and the data suggests that the new material is meeting this criterion based on the class averages and medians and is efficiently balancing scores with the time needed to instruct the material.

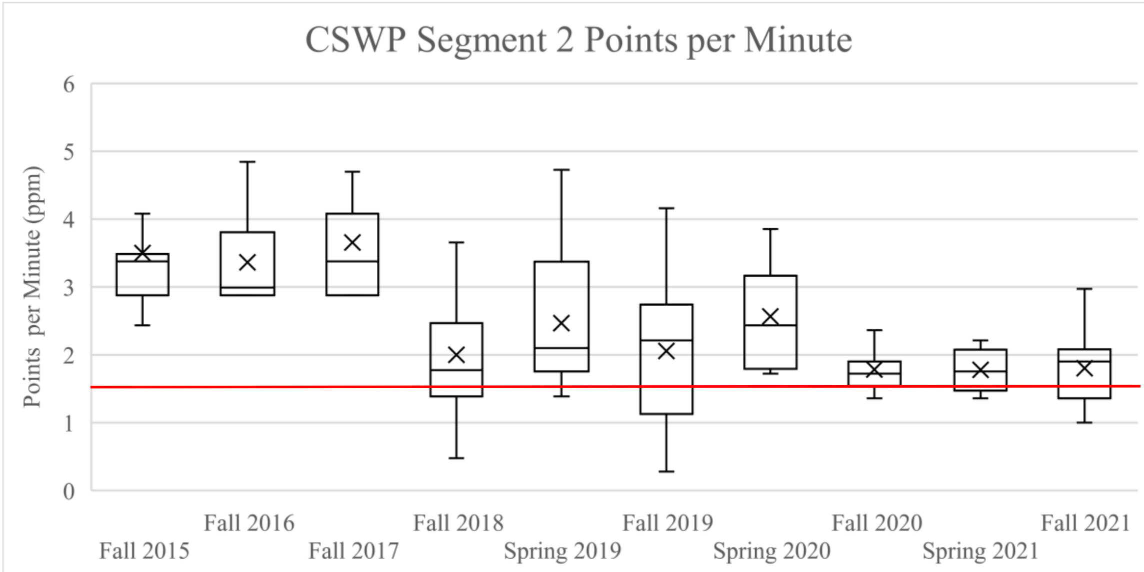


Figure 10: CSWP Segment 2 points per minute

CSWP Segment 3: Assemblies and Advanced Mates

This segment is largely considered to be the easiest segment out of the three and so it is usually taught first and is replaced by CSWP Segment 1. This segment contains only a few new features to students and the most difficult aspect of preparing for this exam seems to be becoming reacquainted with the software. Students leave the base class, *Computer Aided Design Methods*, with their CSWA and are well prepared for this exam when they enter the class. The only features students may not have been exposed to before are width mates, path mates, and gear mates (Figure 11). Each of these advanced mates are used on the exam with gear mates and path mates being a critical component in the learning outcomes of the exam.

Figure 11: Advanced and mechanical mates

Creating material for this section included designing basic models that excel at teaching the tools they are designed for. Figure 12 shows a simplified gear assembly that includes two gears with concentric root diameters and one “tooth” on each gear. This example portrays the advantages and limitations of the gear mate by demonstrating that the mate in Solidworks can be changed to reflect different gear ratios regardless of the number of teeth, that gears don’t have to share a coincident pitch diameter, and that the teeth don't have collision detection naturally enabled so it's up to the student to position the gears in the correct orientation before adding the gear mate.

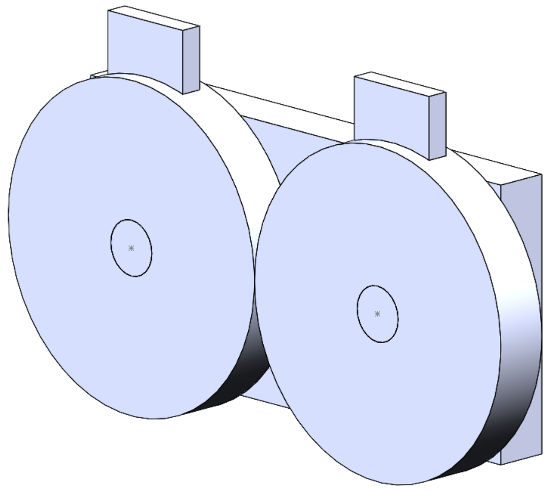


Figure 12: Gear mate example

This segment also utilizes a sample exam for one of the assignments. This sample exam is provided by Solidworks and was evaluated as an exceptional exercise for students to learn how to manipulate flexible assemblies, edit in context mates, look at collision detection, and find part interference volumes between components. Figure 13 shows that students are required to assemble the scissor arm system and find the location where the pivot collides with the base. They are also required to recreate the base from part drawings which provides a valuable introduction to feature order, which is one learning outcome in the CSWP Segment 2.

Figure 13: Scissor assembly sample exam

CSWP Segment 3 pass rates (Figure 14) saw a consistent grouping of 100% pass rates from Spring 2019 to Spring 2020 with a sharp decrease in Fall 2020 and slight increases afterward. The average pass rate across all semesters is 84.8% and 87.3% across the most recent five semesters. This exam has been believed to be dominated by the success of the previous Solidworks course because this is the first exam to be taught in the advanced course. This could be partially true, but the introduced material is designed to reduce failures regardless of a student's ability coming into the course. The data supports the claim that the new material doesn't do an adequate job of preparing students compared to previous material, so it is suggested to reevaluate the old material for what is beneficial and incorporate those features into the curriculum. Additionally, it is suggested that spending more classroom time reacquainting students with the tools in Solidworks would be a beneficial addition to the curriculum. If outlier data for Fall 2021 is disregarded, the pass rate increases to a point where the data falls into normal student variation.

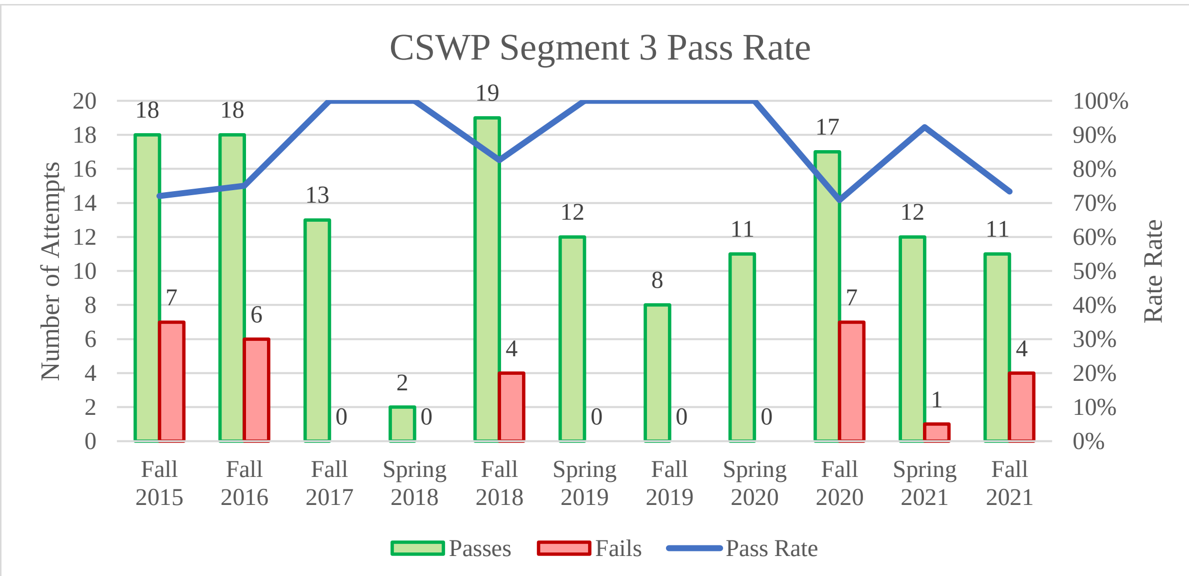


Figure 14: CSWP Segment 3 pass rate and number of pass/fail attempts

When looking at the CSWP Segment 3 points per minute from previous semesters located in Figure 15, there is a very noticeable drop in ppm after Fall 2017 and scores generally sit right above the minimum passing ppm of 0.96. This correlates with the adoption of *Certified SOLIDWORKS Professional Advanced Preparation Material* and a shift in the class toward the CSWPA exams. This change also affected the teaching schedule for each exam. The time spent per exam in the Fall semesters of 2015-2017 was several weeks compared to a week or two for the later semesters. Something important to note is student ppm seems relatively unaffected by the new material introduced in later semesters. This indicates that the material is doing an adequate job of maintaining student scores while under an even shorter time frame than the semesters between Fall 2018 and Fall 2020.

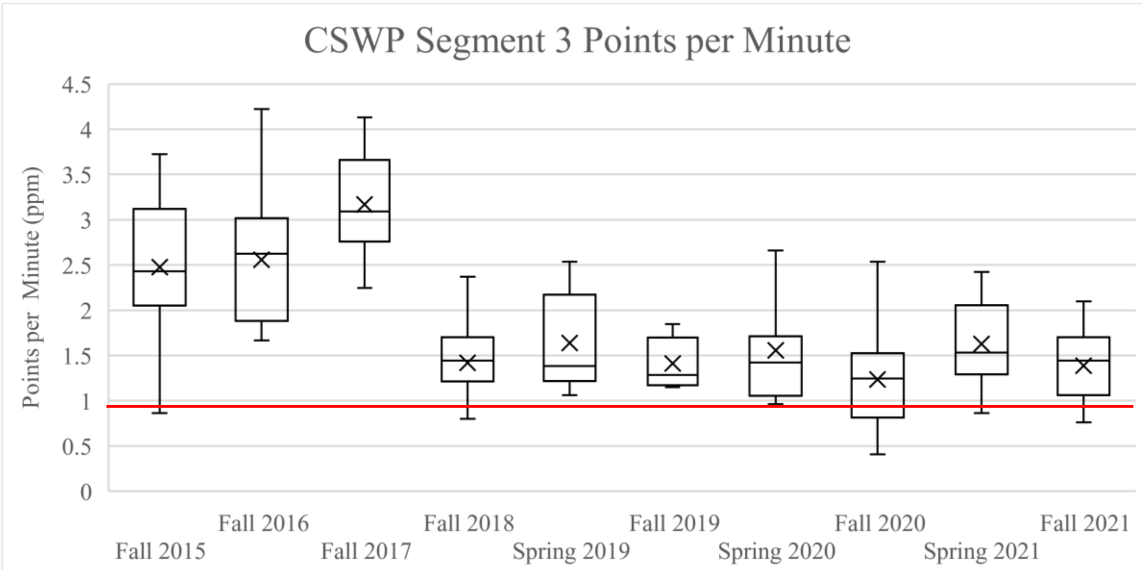
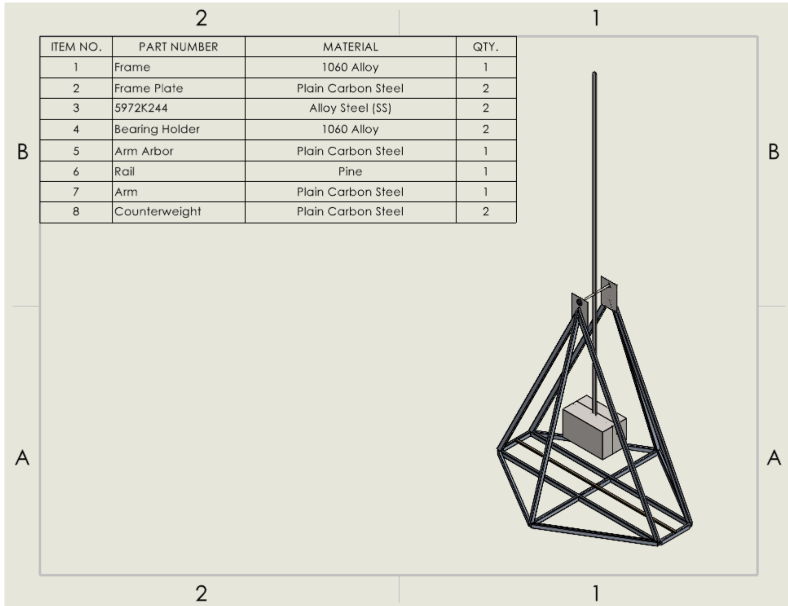


Figure 15: CSWP Segment 3 points per minute

CSWP-A Drawing Tools

This exam is an interesting oddity because it covers view manipulation on drawings and Bills of Materials (BOMs) and doesn't focus on adding common drawing standards to drawings or communication tools like GD&T callouts or welding symbols. View manipulation includes adding features like aligned section views and finding accurate projections for auxiliary and projected views. The BOM features in the exam include using the built in Excel-like cell equation features to incorporate part custom properties. Students will create BOMs to find total costs of assemblies, part quantities, and distinguishing features about certain parts like applied surface conditions.

Figure 16 details an example in the assigned homework that has students create a BOM and find the total cost of the trebuchet in two configurations that have different counterweights. This example exposes students to all the BOM features on the exam. This example is good because it allows students to experience potential problems with the equation manager and custom properties before they encounter them during the exam.



ITEM NO.	PART NUMBER	MATERIAL	QTY.
1	Frame	1060 Alloy	1
2	Frame Plate	Plain Carbon Steel	2
3	5972K244	Alloy Steel (SS)	2
4	Bearing Holder	1060 Alloy	2
5	Arm Arbor	Plain Carbon Steel	1
6	Rail	Pine	1
7	Arm	Plain Carbon Steel	1
8	Counterweight	Plain Carbon Steel	2

Figure 16: Trebuchet BOM example

Students are also given a drawing tools sample exam to complete that is released by Dassault Systèmes. The sample exam covers another example of creating a BOM, has students find true and projected angles on drawing views, and exposes students to looking at a foreshortened view. The foreshortened view shown in Figure 17 changes a section view from an unfolded normal view to a projected normal view.

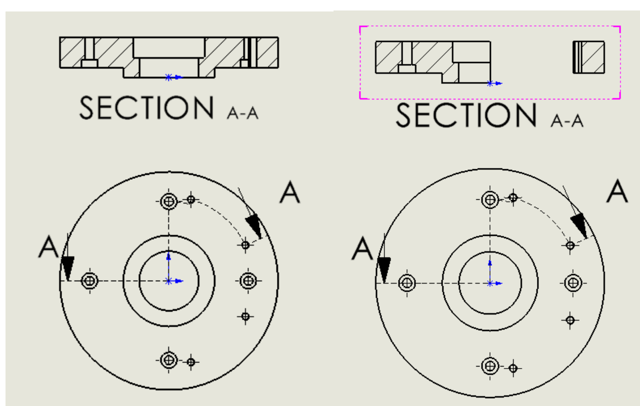


Figure 17: Traditional section view (left) versus foreshortened section (right)

Student pass rates for the CSWPA Drawing Tools exam can be seen in Figure 18. The average pass rate across all semesters is 93.5% and 91.0% over the past five semesters. Failure rates have been very low for most semesters but have spiked in the past year. The number of failed attempts for 2021 shows that more time needs to be spent on the topics covered in the exam. Student feedback within class has indicated that the introduced homework covers the topics on the exam, so more attention needs to be paid to student understanding.

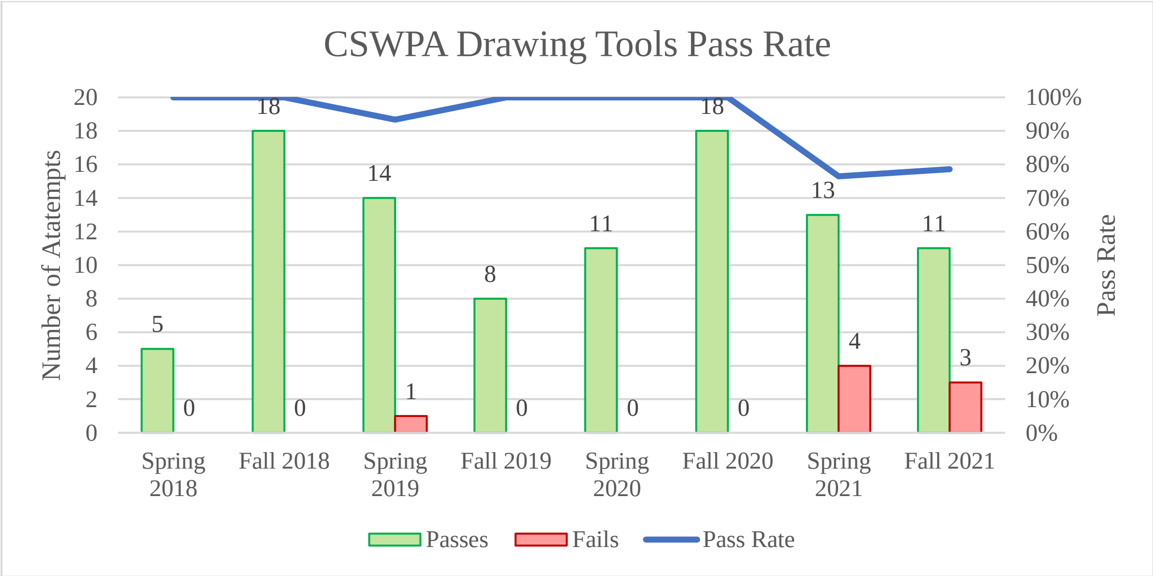


Figure 18: CSWPA Drawing Tools pass rate and number of pass/fail attempts

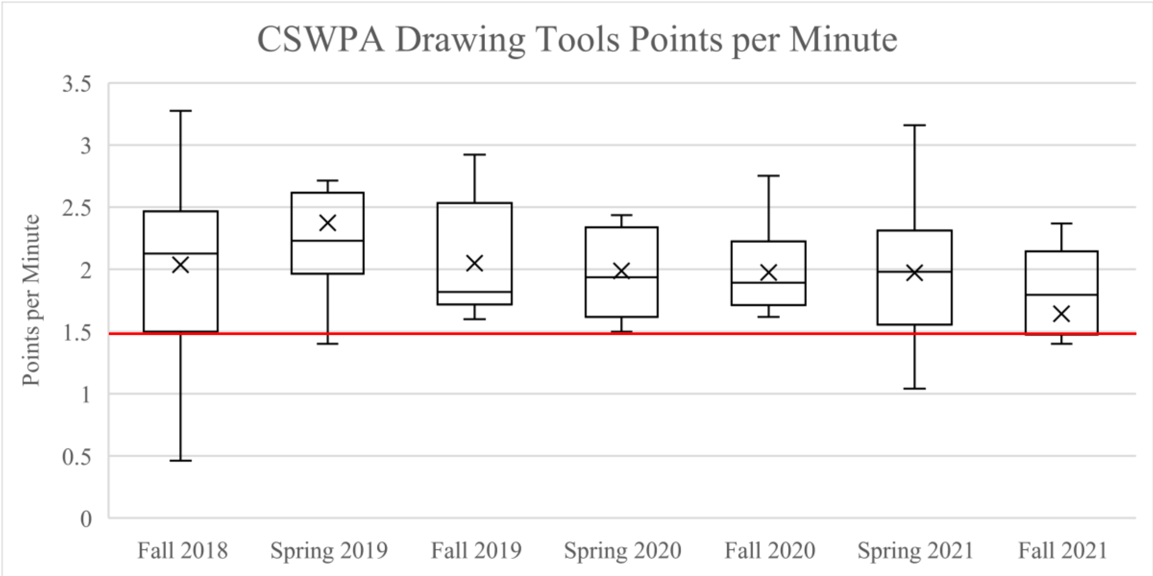


Figure 19:CSWPA Drawing Tools points per minute

When examining student exam scores regarding ppm, found in Figure 19, the results have been very consistent across semesters. The required ppm to pass is 1.5 and the majority of student ppm sits above this cutoff across every semester. The introduction of new material in the later semesters seems to have achieved the desired result of maintaining student scores. Further action in this section can be taken to reduce ambiguity with the tools with the goal of reducing variation in student scores.

There is one additional focus area in this section that spans the entire semester. It is believed that selected topics in the exam do not completely cover important tools and features in Solidworks that are used in industry [10], so a third of class time throughout the course is devoted toward teaching students how to correctly interpret drawings and their related standards in the machine shop. This offers students the opportunity to understand the importance of different dimensioning tolerances and types while also allowing students to gain hands on experience with manufacturing equipment. This content area is designed to help fill out areas of understanding that would not be possible through exclusively lab-taught material. Students find the skills they learn in this content section to be extremely valuable and aids their understanding of important considerations in the manufacturing process and also how to communicate design intent through their drawings.

CSWPA Sheet Metal

The sheet metal exam covers topics around the bending, cutting, and forming of sheet metal. Parts can be easily designed for sheet metal applications and with this feature, the program does many calculations and considerations for the use automatically like creating bend radii and finding flat pattern areas. Students in this section learn how to create sheet metal parts and how to import other file types to enable part modification. This exam challenges students to pay attention to details because answers are highly dependent on how features are dimensioned.

All content for this section was created to explain the tools and concepts surrounding the problems on the exam. The example problem seen in Figure 20 below shows the importance of looking at details. Features are dimensioned off different sides of the sheet metal which is something that is found on the exam. Students also are exposed to gauge tables, which are a convenient way to organize sheet metal parameters through Excel, much like design tables.

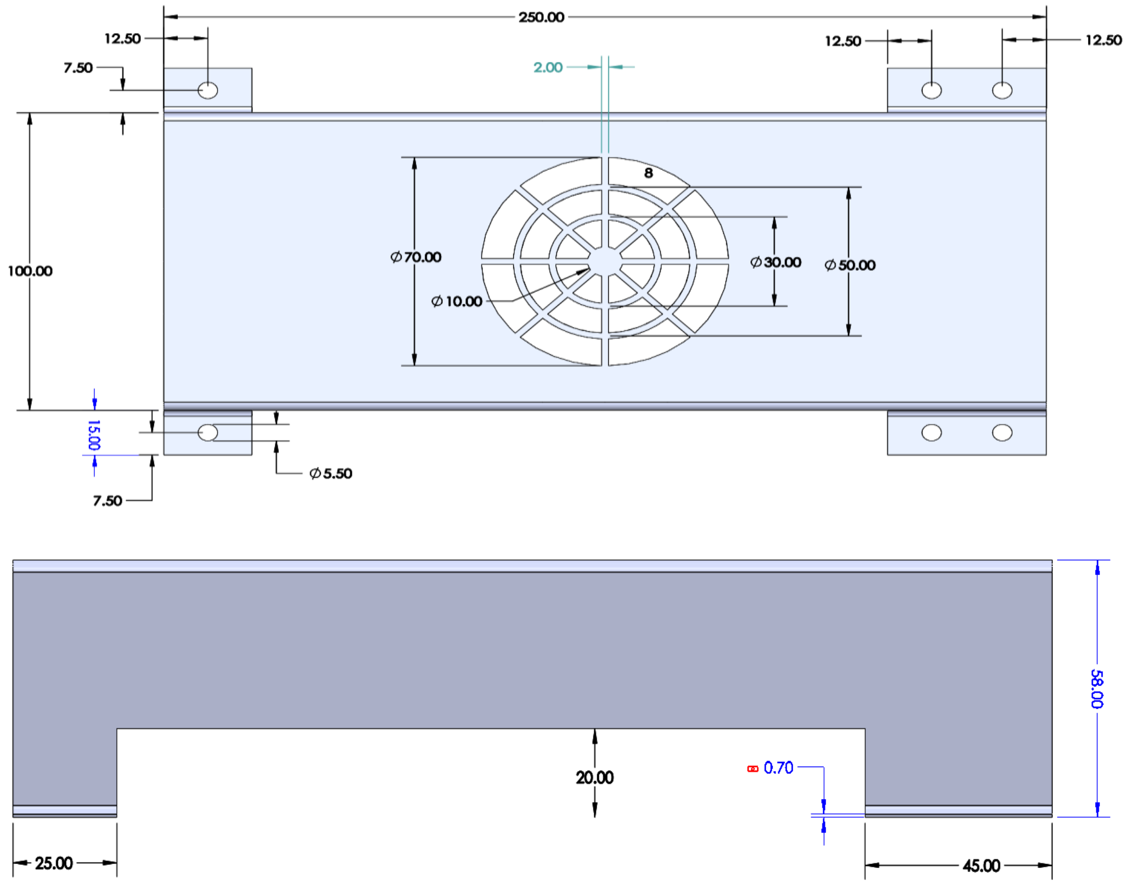


Figure 20: Vent cover sheet metal exercise

Interacting with other file types and software is an important part of working with customers and suppliers. Solidworks supports importing many file types, but sheet metal parts have a uniquely hard time being imported because of a part healing option. Solidworks will try to "heal" a part that is being imported by default and this leaves major features of the part unrecognizable within the software. Knowing why Solidworks heals files helps students understand potential errors that could be happening. At this point in the semester, students should be comfortable diagnosing and repairing sketch and feature problems and are ready to move on to solving more advanced problems like the auto heal option seen in Figure 21.

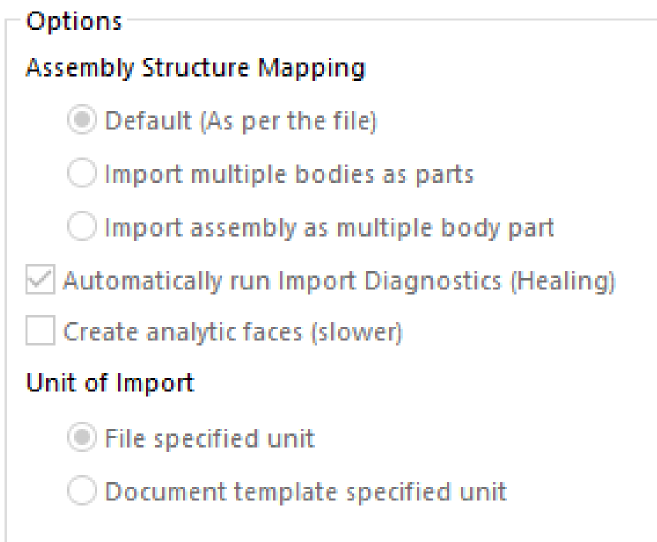


Figure 21: Import diagnostics healing feature

Figure 22 shows the CSWPA Sheet Metal pass rate. The average pass rate across all semesters is 82.55 and 77.6% across the previous five semesters. The new material developed for this exam was introduced in Fall 2021 and if certain outlier data is excluded, the sheet metal exam scores return to relatively normal levels, but more time should be devoted to student understanding for scores to be improved further.

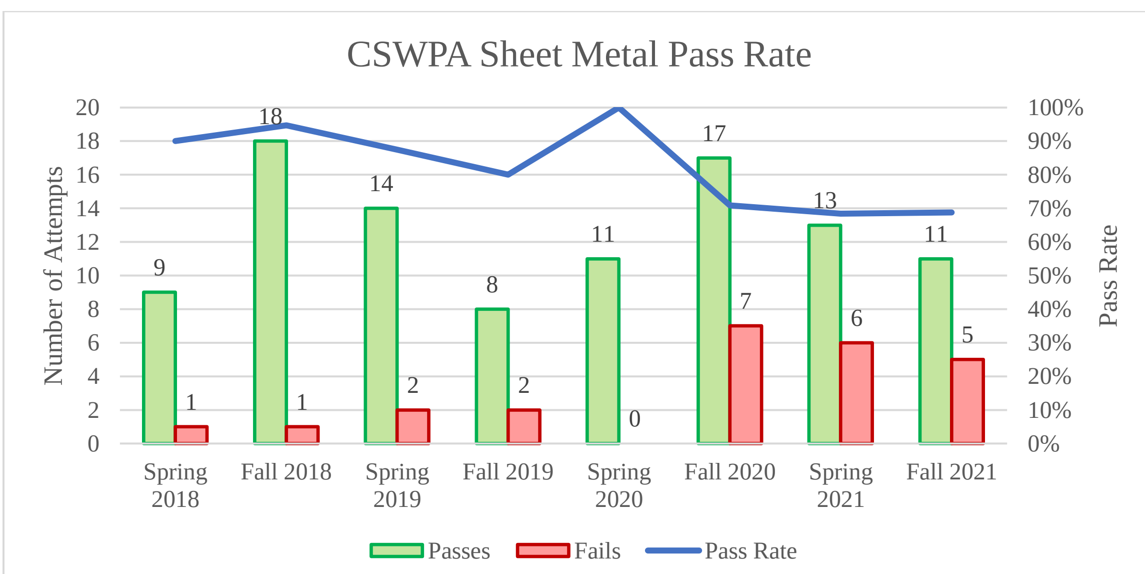


Figure 22: CSWPA Sheet Metal pass rate and number of pass/fail attempts

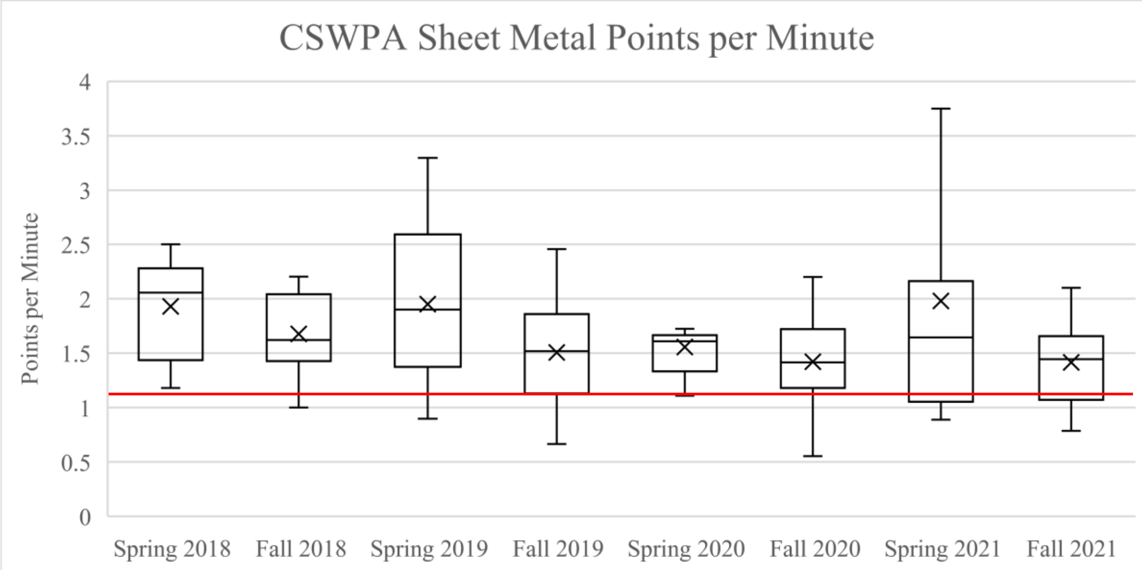


Figure 23: CSWPA Sheet Metal points per minute

The CSWPA Sheet Metal scores from previous semesters (Figure 23) are keeping the trend of staying relatively unchanged after the introduction of new material. The minimum ppm required to pass is 1.11 ppm and every semester has seen the majority of scores above this cutoff. The time taken to teach this exam in recent semesters has been reduced to one week. Variance in student scores have remained similar to previous semesters but can still be reduced through constructing homework problems to state more clearly what is being asked and for in class examples to have more student participation and follow along.

CSWPA Weldments

The Weldments exam covers topics like bar and tubing extrusions, complex 3D sketching, and projected versus true angles. The tools in this section allow the user to quickly create frames in Solidworks that are designed to be welded and are broken into items that have predefined cut lengths. Students in this section learn to create custom weldment profiles, modify weld joints, and define the weld gaps that would be necessary for the frame to be completed.

The preparatory material for this exam has students create weldment profiles in various shapes, thicknesses, and sizes for repetition to help in understanding the difficult file paths necessary to introduce a custom profile. This is a complicated process that involves changing default Solidworks libraries to include user created ones. Figure 24 provides an example of how a custom profile can be added to a 3D sketch to create a structural member.

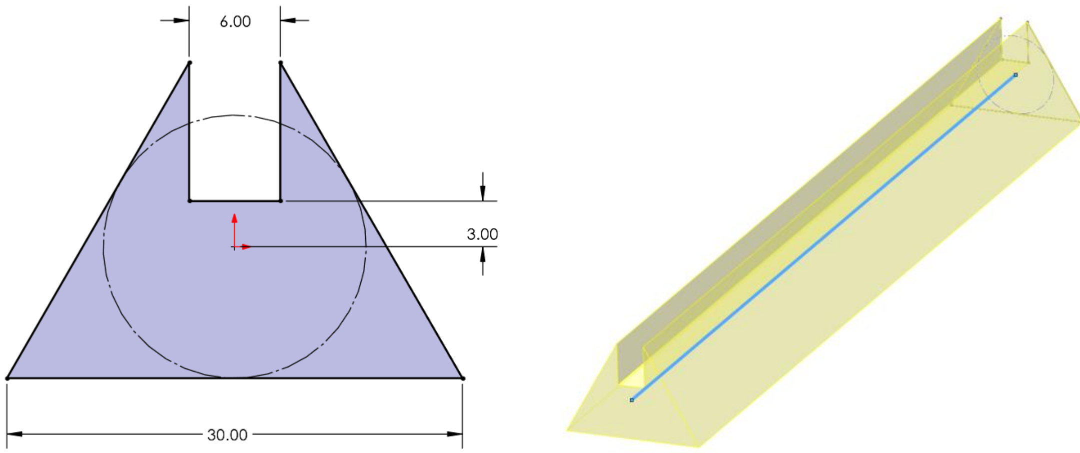


Figure 24: Custom weldment profile and structural member example

One major part of this section is to understand how to draw sketches in 3D. Students will have been exposed to 3D sketching in the Surfacing section previously in the semester, but this content has them exploring the topic further. Students learn that 3D sketches have six degrees of freedom which requires sketches to be constrained in many more dimensions. Figure 25 shows how a tradition circle must be rotationally constrained when being drawn in a 3D environment. Additionally, relations are no longer automatically shown so students must rely on memory and checking items individually for constraints.

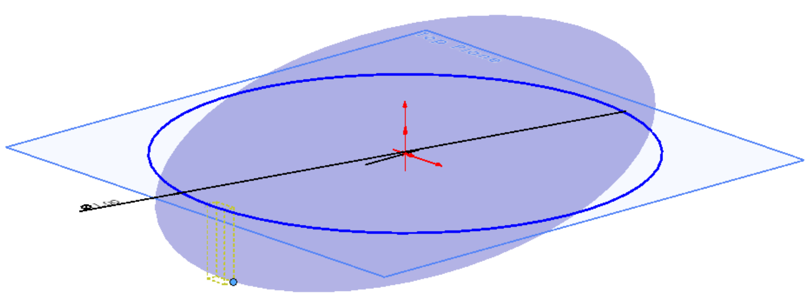


Figure 25: Constraining a circle in plane for 3D sketching

The developed material includes 3D sketching challenges like the one seen in Figure 26 as well as making frames, like the one seen in figure 27. Complicated options like joint order, weld gaps, and member orientation are covered to help student understanding of weldments and to prepare them for similar problems on the exam.

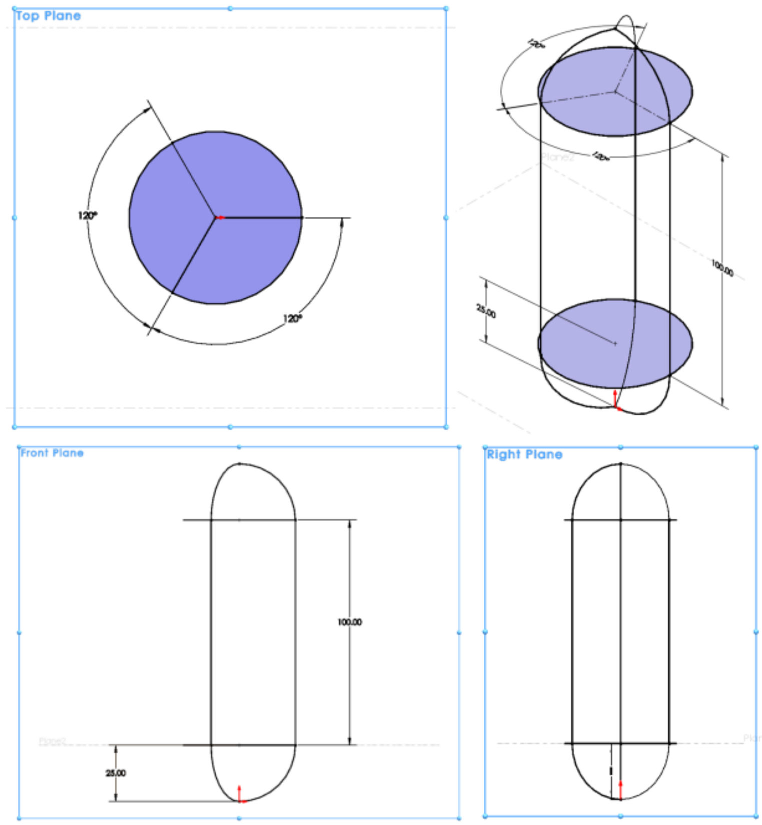


Figure 26: Bird cage 3D sketching example

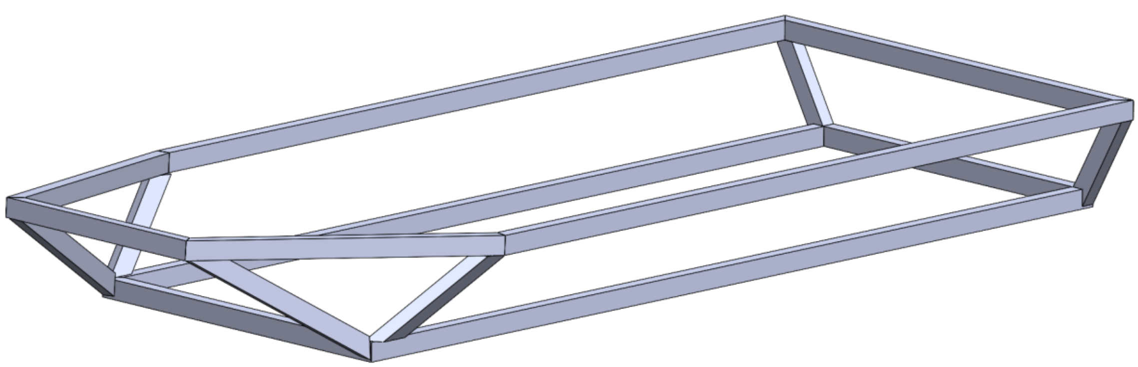


Figure 27: Boat weldment frame

Figure 28 shows the CSWPA Weldments pass rate. The average pass rate across all semesters is 91.1% and 88.6% across the five most recent semesters. Due to Fall 2020 being such an unusual semester, it's important to note that the average pass rate across the course is 94.6% when excluding that semester. Pass rates for this exam have been high across most semesters and the average pass rate is very high compared to all the other exams. Overall, it is recommended to keep the developed material due to the high pass rates on the exam.

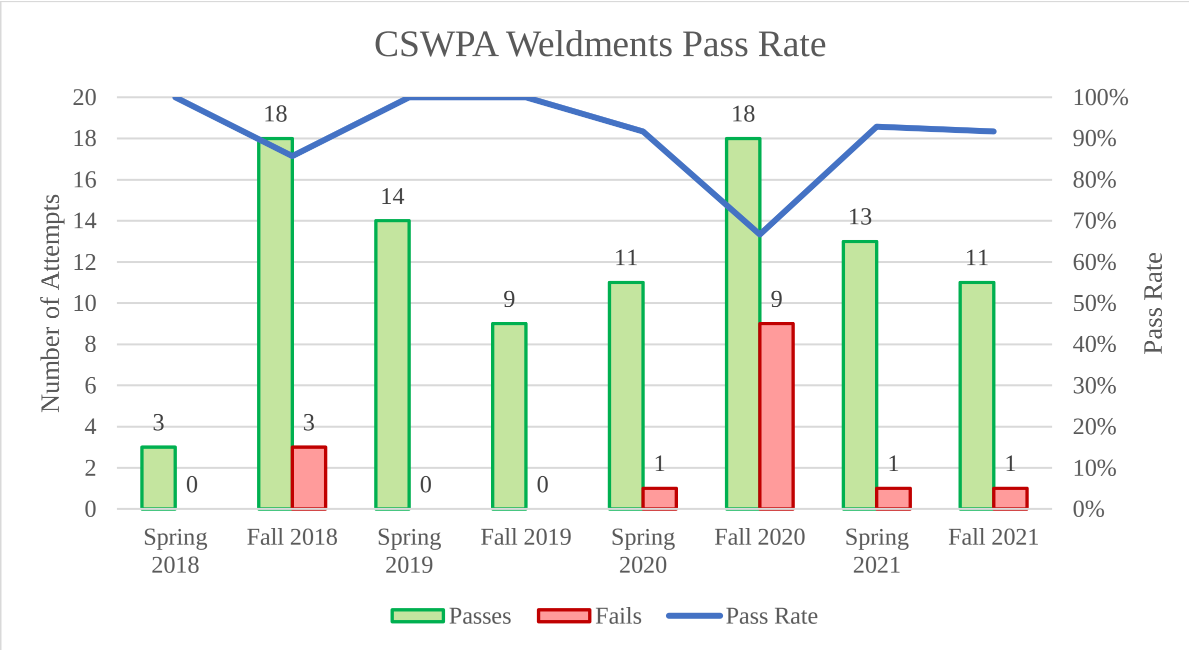


Figure 28: CSWPA Weldments pass rate and number of pass/fail attempts

Figure 29 below shows the CSWPA Weldments exam points per minute. The minimum required ppm for this exam is 1.58 and the majority of student ppm lies above the cutoff. The points per minute of the exam in the past semesters indicate a large drop in score per minute after the bookwork was introduced and, as previously theorized, it is believed this is due to the reduction in time lecturing on material. This section has been reduced to two weeks with one week spent lecturing on 3D sketching and one week spent teaching the tools in the Weldments section. As specialized material has been introduced, the average score of the class has been steadily increasing from 1.92ppm to 2.15ppm, indicating that the new material has improved scores beyond the examples presented by the book.

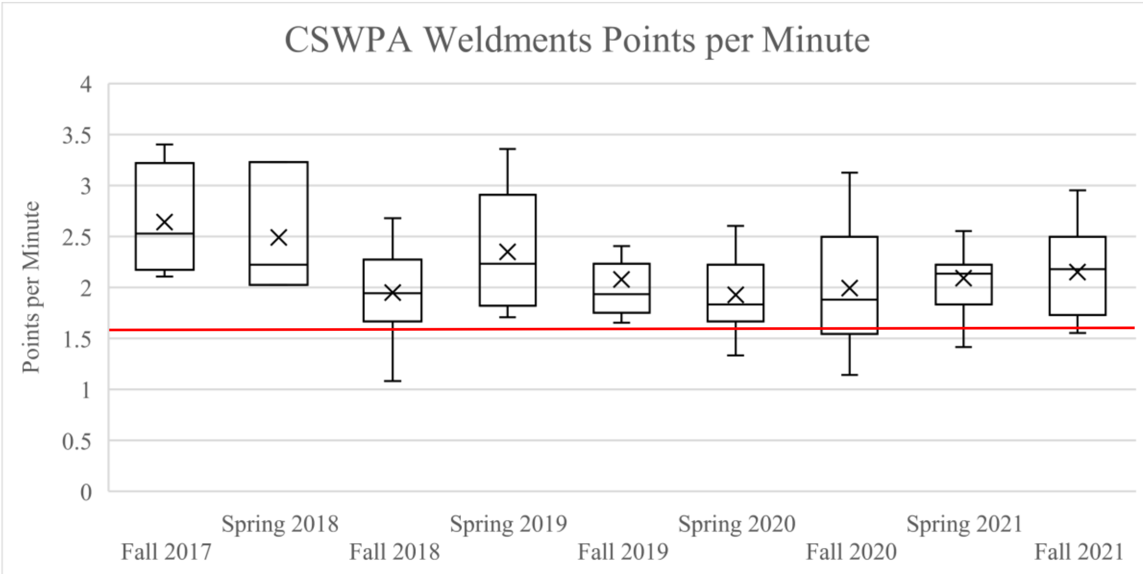


Figure 29: CSWPA Weldments points per minute

Conclusion

The scope of the *Solid Modeling, Simulation and Manufacturing Capstone* course has changed significantly since its introduction. The course started with covering the three section exams in the CSWP and then moved on to include four of the CSWP Advanced exams and then moved even further to include the CSWE exam, the pinnacle of Solidworks certifications. Because the scope of the course has changed so significantly, the material required to instruct students has also needed to adapt to include the required material. This new material, created for the class over the past two years, has data supporting the claim that students are better or equally prepared for the exams compared to previous material, while being under a reduced instructional timeframe. Pass rates for the CSWE have increased dramatically [7] because of time that was made during the normal curriculum. Further action can be taken to increase scores by increasing the number of problems that students must complete in a given time frame and by listening to student feedback about material that could be taught differently or more completely.

Chapter 4: Using Solidworks as a Research and Design Tool

Introduction

This purpose of this chapter is to show how Solidworks can be used as a design tool at an expert level with a case study of a mechanical clock. The details of process will be explained more in in the next chapter the purpose is to use Solidworks to model and optimize the chosen clock to develop a timepiece that works intelligently, efficiently, and correctly.

Designing a Mechanical Clock

Mechanical clocks have classically been seen as a pinnacle of mechanics. They include complex gear trains with many moving parts and sliding surfaces along with a requirement of being highly accurate. They could even be described as beautiful in their function. Unfortunately, mechanical clocks can be difficult to understand and are usually unique in their construction. Luckily, products like Solidworks offer a solution to reducing the complexity of designing a mechanical clock by allowing the user to visualize the entire system and calculate physical properties that would be tedious in real life. Figure 30 shows an Epicyclic Strutt Clock designed by W.R. Smith (1921-2016).

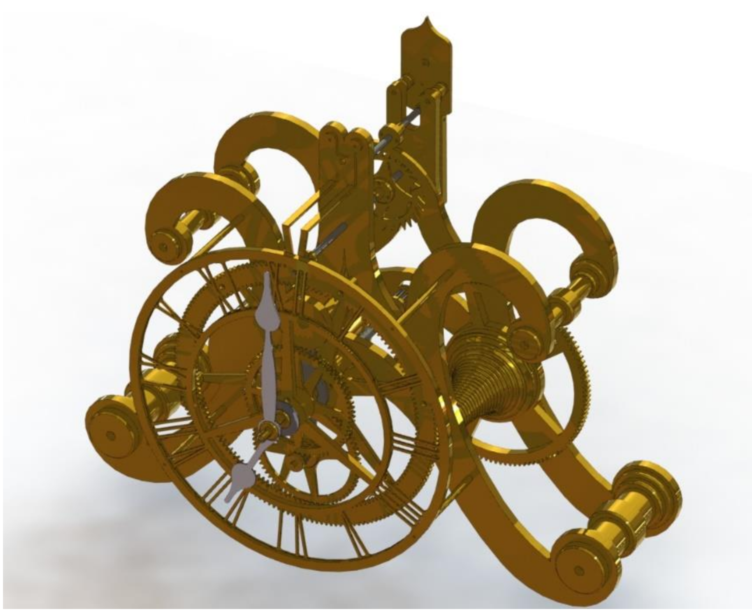


Figure 30: Epicyclic Strutt clock

The clock features a planetary gear system, a spiral spring to provide energy, a pendulum for energy storage and for a consistent periodic time, and a special torque mechanism called a fusee, which will be discussed next. This clock is, for a mechanical system, a perfect case to analyze. Theoretically, a horologist can take inertial values from the gear train and find the minimum and maximum torque values that would allow the clock to function. To correctly analyze the clock however, the fusee must be correctly modeled in Solidworks which requires a torque estimate. Measurements of the actual Strutt clock made by Smith provide a minimum torque requirement of 3 in-lbf, but this measured post construction. With the gear analysis by the horologist, an ideal torque can be chosen beforehand, allowing the fusee to be derived before construction begins.

Chapter 5: Developing a Method for Designing a Clock Fusee Using TK Solver 50

Introduction

W.R. Smith (1921-2016) was a master clock maker who made mechanical clocks throughout the 20th century, including a series of brass skeleton clocks [4]. A characteristic that Smith incorporated into these brass skeleton clocks is a mechanism called a fusee. A fusee is a truncated, concave, parabolic, threaded cone, and acts as a pully to convert a diminishing torque curve into a constant torque, and therefore constant acceleration, in the gear train. The fusee mechanism is designed to be used with a secondary mechanism comprised of a spiral spring enclosed in a barrel. These two mechanisms work in tandem to power the clock and maintain a consistent time. The fusee is mechanically attached to a gear that drives the gear train. The enclosed spring, located in the barrel, drives the fusee and provides energy to the clock. The shape of the fusee has classically been tasked to horologists, or master clock makers, because of its complexity and its difficulty to manufacture or alter. The goal of this chapter is to make the fusee mechanism more available to the horological community, hobbyists, and ultimately to the general public and to give them a tool to use when designing their clocks.

Defining a Fusee

The equations defining a fusee are bound by distinct variables relating to the pitch and size constraints of the fusee, size and strength of the selected spring, and the dimensions of the barrel and arbor. These are engineering choices that are made during the creation and design of the system that the fusee and barrel accompany. The governing equations of the fusee have been derived by several parties, including Rawlins [3], Powell [11], and Preisendorfer [12]. Rawlins was the first to approximate a solution for the shape of the fusee in 1974 and was followed by Powell in August of 1975 and Preisendorfer in October of the same year.

Rawlins developed his solution and put it in his book, *The Science of Clocks and Watches*. The book served to provide an educational base for those looking to study horology. Rawlins solution works but did not contain a change in radius term. Powell believed, rather strongly, that this was an egregious error and proceeded to release his own solution that contained a change in radius component. After this release, Preisendorfer, a well-respected mathematician, took Powell's solution and improved it further to include a pitch term, effectively creating a 3D Pythagorean theorem in polar coordinates. Preisendorfer's release highlighted the error in both previous solutions while also commenting on Powell's unprofessionalism with regards to Rawlins's release. Ultimately, it was determined that the effective difference between the three solutions is negligible and that the solutions differed by a couple ten thousandths over the length of the fusee chosen by Smith.

Before discussing any derivations, it is important to establish a common set of variable labels. These labels are listed in Table 2 below with a helpful visual for some of the more important variables in Figure 31.

Table 1: List of variables in the fusee profile derivation

r	Radius of the fusee
R	Radius of the barrel
φ	Angle of twist of the fusee
Φ	Angle of twist of the barrel
ρ	Pitch of the fusee
P	Pitch of the barrel
x	Length along the fusee
X	Length along the barrel
T	Torque from the barrel
k	Spring constant of the mainspring
s	Length of wire wrapping the fusee
S	Length of wire wrapping the barrel
F	Force exerted by the mainspring

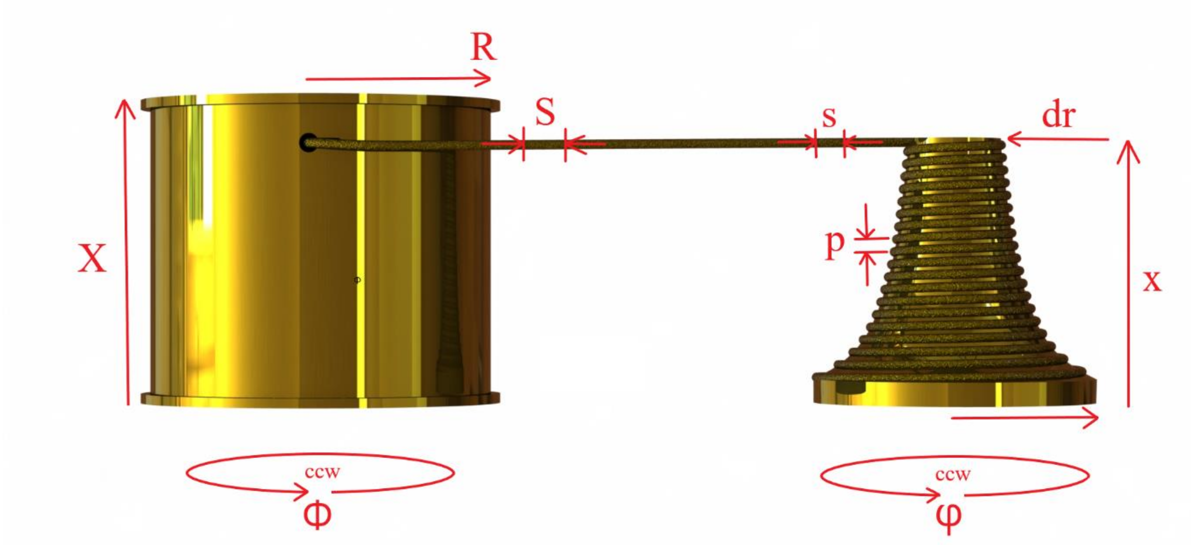


Figure 31: The interaction between the fusee and the barrel

The equation defining the profile of the fusee can be solved as a function of x or of φ. Rawlins solves the radius function with regards to total turns while Powell solves the function with regards to x. The following derivation will use Preisendorfer's notation by solving the radius as a function with respect to the fusee rotational displacement measured in radians. The equation that drives the shape of the fusee must have two key factors: variables for the change in radius and the change in angular displacement as well as the force and spring constant from the mainspring. Three fundamental equations were chosen so that, in combination, they would be able to satisfy these two conditions for the complete profile. The first among the three equations is the arc length formula. Equation (1) describes the surface arc length relationship between the fusee and the barrel.

$$ds = dS \tag{1}$$

Equation (2) describes the magnitude of the surface arc length of the fusee and its components of radius, change in radius, and pitch. The components are all based on the change in angular displacement of the fusee and define its three methods of change. This is in essence, the Pythagorean theorem in polar coordinates.

$$ds^2 = (r(\varphi) * d\varphi)^2 + (r'(\varphi)d\varphi)^2 + (\rho * d\varphi)^2 \tag{2}$$

Equation (3) defines how the surface arc length of the barrel is calculated as a function of Φ and it is important to note that R is a constant. R being held constant is assumed because in realistic scenarios, varying the radius of the barrel does not positively affect the mechanics of the system and only serves to complicate the clock. The complex profile of the fusee alone is enough to complete the normalization of the torque curve. The radius of the barrel being a constant means that the change in radius term equals zero. The pitch term also drops because it is assumed that the pitch of the barrel is zero due to the near perfect angle it leaves the barrel.

$$dS^2 = (Rd\Phi)^2 + \left(\frac{dR}{d\Phi}d\Phi\right)^2 + (Pd\Phi)^2 \tag{3}$$

With the consideration of the constant radius and that the angle of cable leaving the barrel to be perpendicular to the edge of the barrel, Equation (3) becomes Equation (4)

$$dS^2 = (Rd\Phi)^2 \tag{4}$$

Equation (5) isolates ds and converts $r'(\varphi)$ from Lagrange notation to Leibniz notation which will be useful later when solving the eventual differential equation.

$$ds = d\varphi\sqrt{r(\varphi)^2 + \left(\frac{dr(\varphi)}{d\varphi}\right)^2 + p^2} \tag{5}$$

Equation (6) substitutes Equations (4) and (5) into Equation (1).

$$d\varphi\sqrt{r(\varphi)^2 + \left(\frac{dr(\varphi)}{d\varphi}\right)^2 + p^2} = Rd\Phi \tag{6}$$

Equation (6) is the final variation of the arc length formula and is important because it relates the angular displacement of the fusee to the angular displacement of the barrel. This will be used alongside the Torque Law to relate the change in radius to the change in angular displacement of the fusee.

The next axiomatic equation is Hooke's Law in polar form. Hooke's Law in polar form defines the force of a spring based on its spring constant and its displacement. Spiral springs, like the one used in the skeleton clocks, produce force based on their angular displacement. Because the spring found in the clock is mechanically linked to the barrel that encloses it, the barrel can be assumed to act like a spring when wound. Equation (7) describes the force on the fusee exerted by the mainspring in the barrel.

$$F(\Phi) = F_0 + k\Phi \tag{7}$$

Equation (8) is the derivative of Equation (7). Equation (8) is kept in Lagrange notation to aid in substitution later.

$$F'(\Phi) = k \tag{8}$$

Hooke's law is an important equation because the fusee would not function as desired if it were paired with springs of varying strengths and also because it is necessary to eliminate the number of variables involved. The derivative of Hooke's Law isolates the spring constant term and allows the term to be substituted into the Torque Law later as a constant, simplifying the equation. It should be noted that k is not a perfect constant. In actuality, the constant is drawn from the relative linear portion of a force-displacement graph of the spiral spring and is an approximation. If the exact function of k is known, it can be substituted instead.

The final axiomatic equation is the Torque Law. Equation (9) describes the required torque to drive the system which is equal to the force of the mainspring in the barrel multiplied by the to-be-determined radius of the fusee where the cable between the barrel and the fusee connects.

$$T = F(\Phi)r(\varphi) \tag{9}$$

It is important to note that the force of the mainspring is a function of the angular displacement of the mainspring and is the very reason a fusee is required. The required torque is constant; therefore, the derivative of Equation (9) becomes Equation (10).

$$0 = \frac{dF(\Phi)}{d\Phi} r(\varphi) d\Phi + F(\Phi) \frac{dr(\varphi)}{d\varphi} d\varphi \tag{10}$$

Equation (10) can then be transformed into Equation (11) and then into Equation (12).

$$-\frac{dF(\Phi)}{d\Phi}r(\varphi)d\Phi = F(\Phi)\frac{dr(\varphi)}{d\varphi}d\varphi \tag{11}$$

$$d\Phi = -\frac{F(\Phi)\frac{dr(\varphi)}{d\varphi}}{\frac{dF(\Phi)}{d\Phi}r(\varphi)}d\varphi \tag{12}$$

Equation (13) changes the force derivate in the denominator from Leibniz notation to Lagrange notation and cancels the $d\varphi$ terms. This is the final form of the Torque Law used in this derivation.

$$d\Phi = -\frac{F(\Phi)}{F'(\Phi)r(\varphi)}dr(\varphi) \tag{13}$$

The Torque Law is important because it is the main equation governing the forces in the system. It also brings in $dr(\varphi)$ as a changeable variable and then it relates $dr(\varphi)$ to $d\Phi$.

Substituting the arc length formula into the Torque Law (Equation (6) into Equation (13)) results in Equation (14).

$$d\varphi\sqrt{r(\varphi)^2 + \left(\frac{dr(\varphi)}{d\varphi}\right)^2 + p^2} = R\left(-\frac{F(\Phi)}{F'(\Phi)r(\varphi)}dr(\varphi)\right) \tag{14}$$

Furthermore, substituting Hooke's Law (Equation (8)) and the base form of the Torque Law (Equation (9)) into Equation (14) results in Equation (15)).

$$d\varphi\sqrt{r(\varphi)^2 + \left(\frac{dr(\varphi)}{d\varphi}\right)^2 + p^2} = R\left(-\frac{T}{r(\varphi)^2 k}dr(\varphi)\right) \tag{15}$$

And finally, rearranging and simplifying Equation (15) produces Equation (16)

$$d\varphi = -\frac{RT}{r(\varphi)^2 k\sqrt{r(\varphi)^2 + \left(\frac{dr(\varphi)}{d\varphi}\right)^2 + p^2}}\,dr(\varphi) \tag{16}$$

Equation (16) is the differential equation that relates the change in radius of the fusee $dr(\varphi)$ to the change in angular displacement of the fusee $d\varphi$. One reason this form is desired is because the arc length magnitude term has three distinct terms that each relate to the solutions provided by Rawlins, Powell, and Preisendorfer. Setting the change in radius and pitch terms equal to zero and solving results in Rawlins solution. Setting just the pitch term and solving produces Powell's solution while including all three terms results in Preisendorfer's solution. Having the solution equation in this form aids the user when designing the fusee and selecting which solution type is desirable.

Unfortunately, it is not possible to separate the $dr(\varphi)/d\varphi$ term in the denominator of the right side because of the square root operator. Because the differential equation is inseparable, it is unsolvable through traditional means, but it can still be solved through numerical methods, as is shown in the next section with the Newton-Raphson Method.

The Newton-Raphson Method

The advantage of using numerical methods to solve problems is that exact answers are not required. Solutions can be easily approximated to as many digits as modern computing will allow, which is more than appropriate when considering real world tolerances and manufacturing accuracy. The solution can be approximated using a small $d\varphi$ by breaking the entire rotational displacement into smaller, discrete rotations. This inherently interpolates the ideal solution, but the error of the interpolation can be lowered by decreasing the size of the terms to a point where the real solution and the ideal solution are functionally identical. Additionally, when solving numerically, $dr(\varphi)$ and $r(\varphi)$ turn into interdependent variables that require each other for both to be solved. The interdependent nature of $r(\varphi)$ and $dr(\varphi)$ makes the equation much like life: where it has been determines where it is going.

The Newton-Raphson method is a numerical technique that uses a series of tangent lines that draw closer and closer to the zero of a function until the result falls within a chosen error bound (Figure 32). graphically illustrates how the Newton-Raphson method finds approximations. The approximation p_1 is the x-intercept of the tangent line function at $(p_0, f(p_0))$, p_2 is the x-intercept of the updated tangent function at $(p_1, f(p_1))$, and so on. The method requires a function with a continuous derivative that doesn't equal zero at the initial guess and an initial guess that is a good guess. If the initial guess is not a good guess, the solution may not converge.

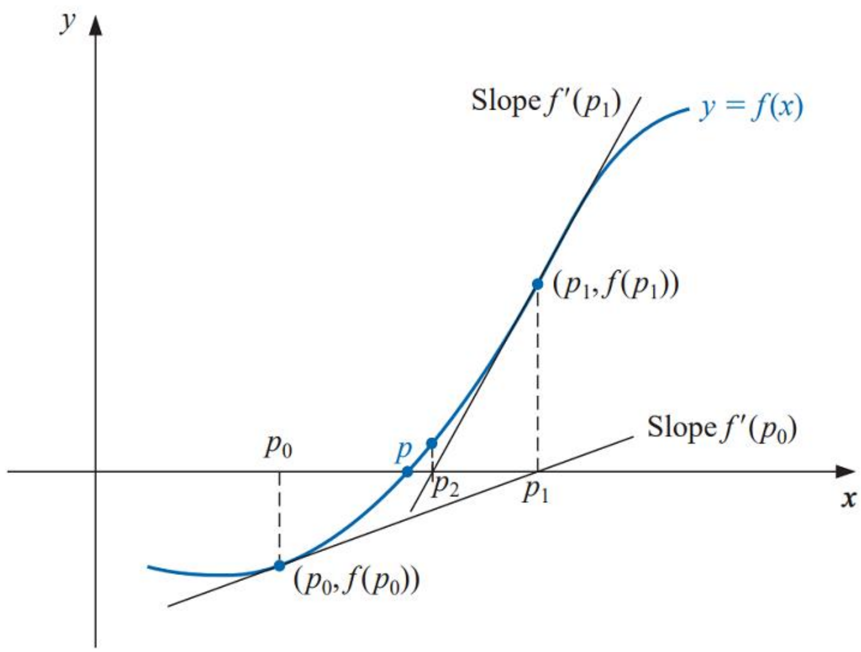


Figure 32: An illustration of finding approximations by using successive tangents. From Numerical Analysis 9th ed. [13]

The proof for the Newton-Raphson method is given in the book *Numerical Analysis 9th ed*. by Burton and Faires [13].

Suppose that $f \in C^2[a, b]$. Let $p_0 \in [a, b]$ be an approximation to p such that $f'(p_0) \neq 0$ and $|p - p_0|$ is "small." Consider the first Taylor polynomial for $f(x)$ expanded about p_0 and evaluated at $x = p$.

$$f(p) = f(p_0) + (p - p_0)f'(p_0) + \frac{(p - p_0)^2}{2} f''(\xi(p)),$$

Where $\xi(p)$ lies between p and p_0. Since $f(p) = 0$, this equation gives

$$0 = f(p_0) + (p - p_0)f'(p_0) + \frac{(p - p_0)^2}{2} f''(\xi(p))$$

Newton's method is derived by assuming that since $|p - p_0|$ is small, the term involving $(p - p_0)^2$ is much smaller, so

$$0 \approx f(p_0) + (p - p_0)f'(p_0)$$

Solving for p gives

$$p \approx p_0 - \frac{f(p_0)}{f'(p_0)} \equiv p_1$$

$$p_n = p_{n-1} - \frac{f(p_{n-1})}{f'(p_{n-1})}, \qquad \text{for } n \geq 1 \qquad (17)$$

The sequence $\{p_n\}_{n=0}^{\infty}$ for the Newton-Raphson method is defined by Equation (17) which assumes $|p_n - p_{n-1}|$ is smaller than a set tolerance as $|p_n - p_{n-1}|$ defines the acceptable error chosen by the user. For most applications, Equation (17) should only need a couple of iterations, depending on the initial guess, to converge to a solution within the error limit.

Solving Using TK Solver

The program TK Solver 5.0 was used to solve Equation (18) with the Newton-Raphson method. Equation (18) adds an acceptable error term to Equation (16) to allow a numerical solution.

TK Solver is a mathematical modeling software that can solve algebraic and differential equations and has multi-directional solving capabilities, allowing it to solve for inputs with pre-chosen outputs. TK Solver also integrates seamlessly with Microsoft Excel, a common spreadsheet software used nearly everywhere.

$$d\varphi = -\frac{RT}{r(\varphi)^2 k\sqrt{r(\varphi)^2 + \left(\frac{dr(\varphi)}{d\varphi}\right)^2 + p^2}}dr(\varphi) + error \tag{18}$$

TK Solver has built-in Newton-Raphson functions that offer different variations of the form seen previously. The function that was chosen was the NewtonN function because instead of needing the exact derivative required by the traditional Newton-Raphson method, the function uses a numerical differentiation which only requires a small differential increment relative to the initial guess value for the chosen equation. TK solver recommends an increment value of 1% of the initial guess value to reduce the probability to guess an incorrect root. The procedure uses the small differential to determine the slope of the error function [14]

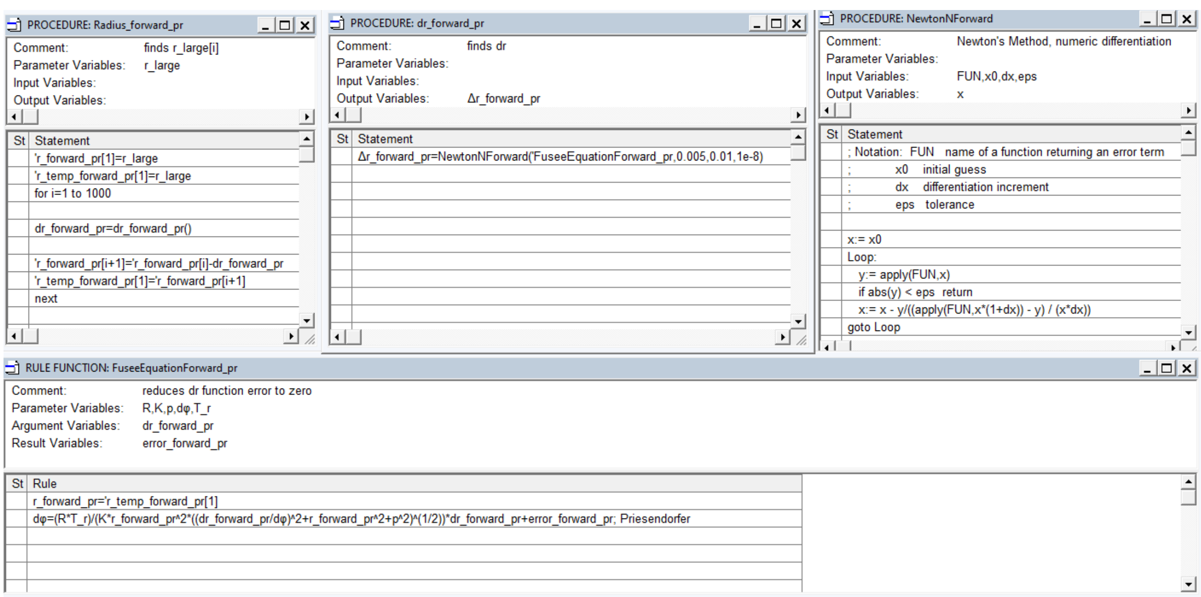


Figure 33: TK Solver 5.0 solution functions

Figure 33 shows the solution path for finding the forward solution for the fusee. A radius index is setup with the *Radius_forward_pr* function with the starting radius being the chosen outside radius of the fusee. The *Radius_forward_pr* then calls the *dr_forward_pr* function to allow the *Radius_forward_pr* function to linearly interpolate the next radius data point in the index. The *dr_forward_pr* function calls the *NewtonNForward* function with the goal of iterating the *FuseeEquationForward_pr* objective function to an error margin below 10e-8. The NewtonN procedure calls the objective function (Equation 16), an initial guess value for the objective function, a small differential increment that changes the value of the guess each iteration, and a goal error tolerance to solve the Newton procedure for. The initial guess for the first iteration is selected based on the constraints set up by the user. The small differential increment is based on this value, as determined earlier. The error tolerance determines the accuracy of the iteration and can increase the quality of the solution at the expense of solution time. Because the NewtonN function is solving for a small error, it will find the "zero" for the error as the Newton method is inherently a zero-finding function. When the error falls within tolerance, the found $dr(\varphi)$ is then used to solve for the next radius term in the index, and the entire iteration begins again. This means that there are four variables being solved simultaneously. The first is the change in slope of the error function which updates the error function as it iterates, second is the error of $r(\varphi)$ as it iterates to zero, third is $dr(\varphi)$ as it iterates with each new $r(\varphi)$, and fourth is the profile radius as it changes from the previous $dr(\varphi)$. The combination of these four variables produces a series of points that, when curve-fitted, produce the radius of the fusee as a function of its angular displacement.

The provided TK code in the digital library found in the appendix also provides the user with plots for the final Preisendorfer fusee profile (Figure 34) along with a plot that relates the forward and backwards solutions for Preisendorfer, Rawlins, and Powell relative to the Preisendorfer solution (Figure 35), which will be discussed next.

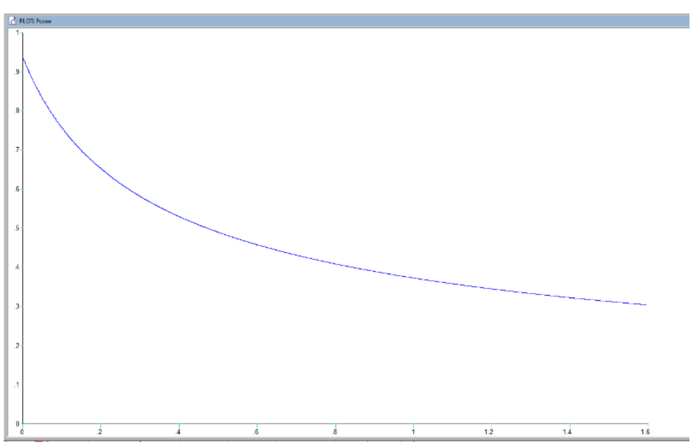


Figure 34: Generated fusee profile in TK Solver 5.0

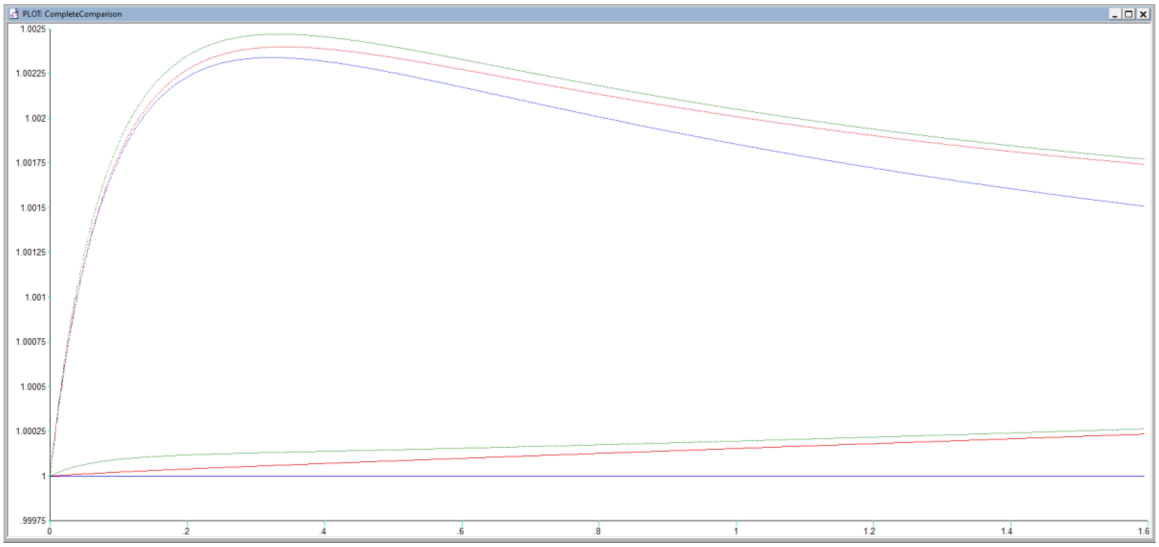


Figure 35: Graphical comparison of the forward (lower points) and backwards solutions (upper poitns) for Preisendorfer (blue), Powell (red) , and Rawlins (green) generated in TK Solver 5.0

Solution and Error Analysis

Now that Equation (18) can be solved, the final solution for the profile of the fusee can be found. Because computation time with modern computing is capable of extremely fast solution times, solving the Preisendorfer variation of Equation (18) with the three included terms of $r(\varphi)$, $dr(\varphi)$, and p takes practically the same amount of time as the Rawlins solution with just the $r(\varphi)$ term while producing a more accurate result. The solution produced by the NewtonN procedure with an initial radius guess of 0.9375in, a differential increment guess of 1%, an error tolerance of 10^{-8}, a torque of 3in-lbf, and a barrel radius of 1.1875in. The torque and barrel radius were chosen based off the Epicyclic Strutt Clock design by Smith. Over a distance of 1.59375in. the equation converges to a final radius of 0.3044in. Figure 36 shows 21 data points along the profile of the fusee along with a sixth-order curve fit to produce an easy equation to manipulate.

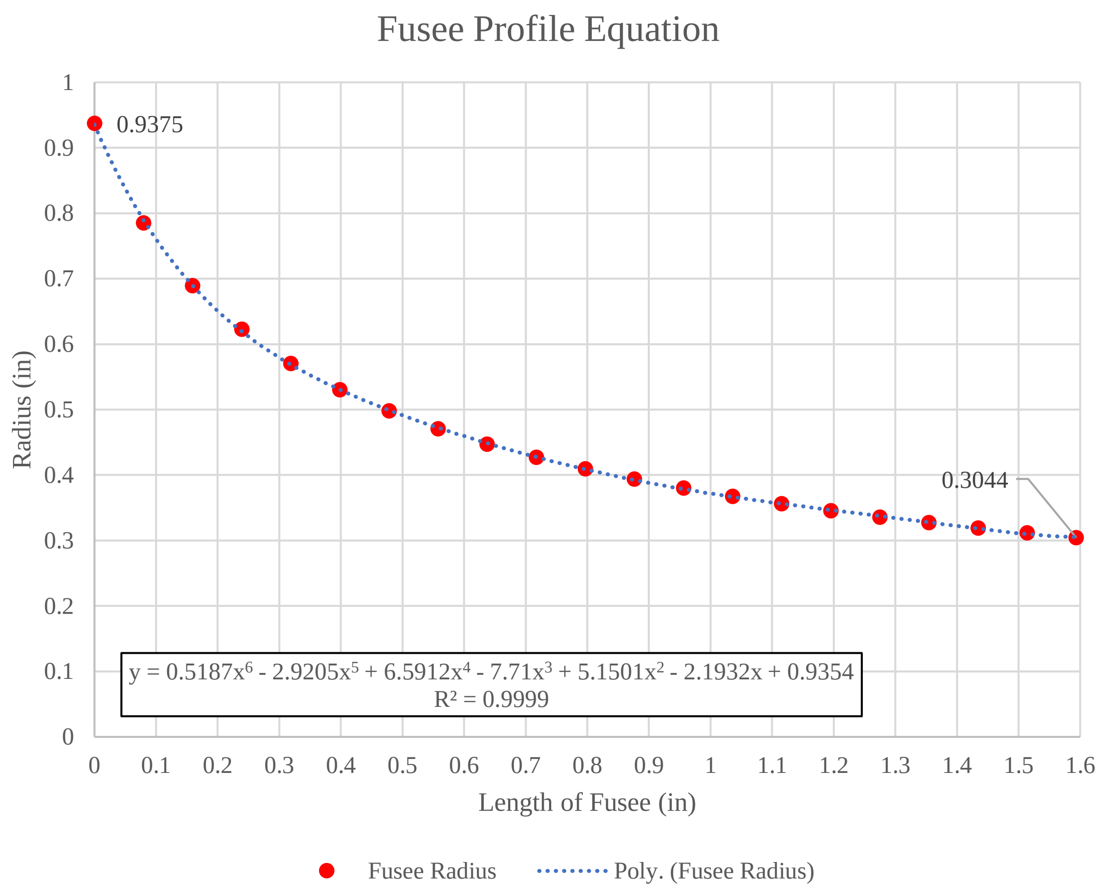


Figure 36: Fusee radius data scatter plot with a 6th order polynomial fit equation

The solution curve is a nonlinear solution with a nonlinear derivative as shown by Equation (16). The left side of the curve is larger because the force of the spiral spring is lowest when it is fully unwound, and it needs a larger radius to compensate while the right side of the curve is smaller because the force of the spring is highest when it is fully wound and the radius on the fusee can be smaller. The polyfit equation was found for the purpose of being used in an online calculator as part of a design aid for users designing around a fusee mechanism.

It is important to look at the Rawlins and Powell solutions to see how they compare to the Preisendorfer solution. By omitting the select terms for each of their solutions, the solution of Equation (18) for Rawlins and Powell can be found. Figure 37 shows the deviation of the Rawlins and Powell forwards solutions normalized to the Preisendorfer forward solution.

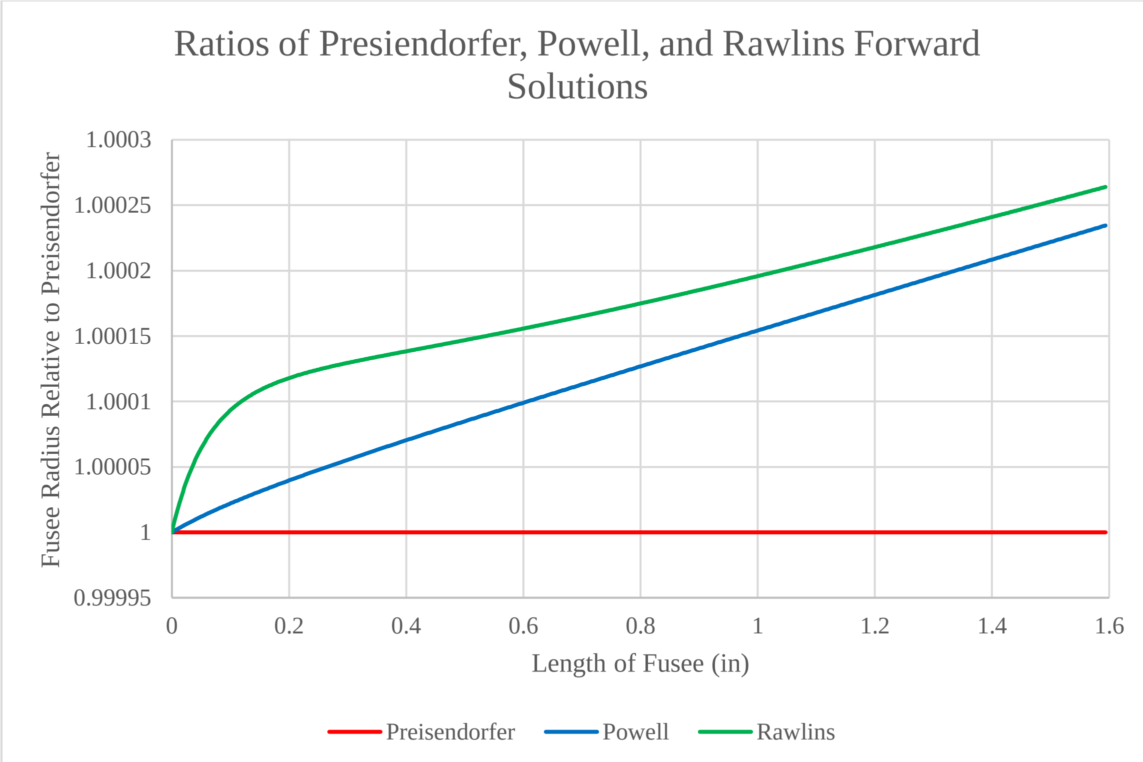


Figure 37: Ratio of fusee solution deviations between Preisendorfer, Powell, and Rawlins in a forward solution

The different solutions show that the inclusion of the extra $dr(\varphi)$ and p terms decrease the size of the fusee. The overall deviation between the three solutions is small relative to the magnitude of the size of the fusee with the chosen boundary conditions and is small enough to not significantly affect the geometry of the fusee or the torque in the system. When factoring the tolerances of modern machinery, only the most accurate CNC machines would be able to reflect the difference between the solutions.

The Powell and Rawlins solutions vary in the slope of the deviation at the beginning when the change in radius is the greatest, showing the effect of the $dr(\varphi)$ term. This variation levels out as the change in slope decreases which agrees with the beginning transient portion of the deviation. While the deviation between the Rawlins and Powell solutions becomes constant, they both increase more linearly compared to the Preisendorfer solution. This linear increase as the length of the fusee increases shows that the introduction of the pitch term adds a constant increase in deviation between the solutions. In the chosen scenario, the final radius difference between the Rawlins and Powell solutions from the Preisendorfer solution are 8.0e-5in and 7.1e-5in respectively.

One factor that should be considered with this type of solution is the direction that the equation is solved, either from left to right or right to left. Equation (18) can be solved backwards by guessing a small radius until the large radius equals the chosen radius within a certain error margin. Solving for each previous derivation backwards and normalizing by Preisendorfer's forward solution produces Figure 38. The reverse solution differs from the forward solution by just under 0.25% at its largest error. The Powell and Rawlins reverse solutions follow a similar pattern to the forwards solutions with a large relative change from the pitch and dr terms followed by a narrow difference between the Powell and Rawlins solutions toward the small end of the fusee. The Rawlins and Powell terms differ by extremely small amounts relative to each other but differ a lot from the Preisendorfer solution. This shows that the inclusion of the pitch term is significant for the reverse solution.

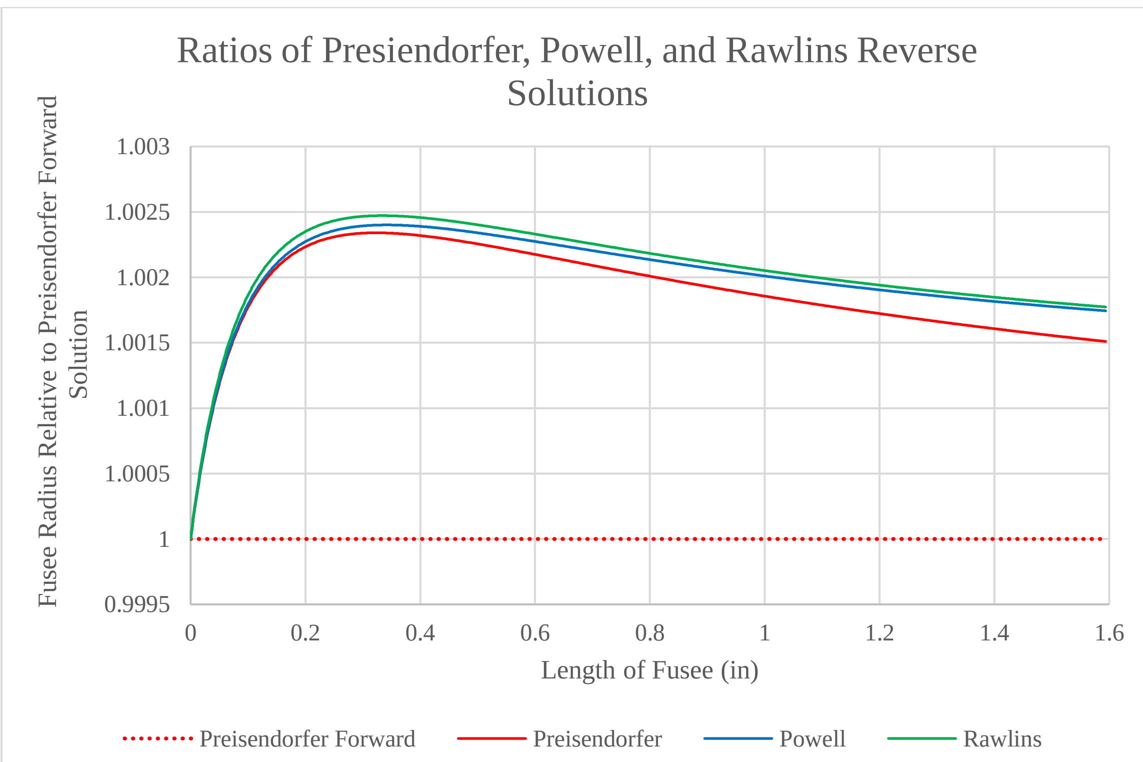


Figure 38: Fusee Solution Deviations between Preisendorfer, Powell, and Rawlins in a reverse solution relative to Preisendorfer's forward solution

When applied to a clock, the variation in the solutions could conceivably become significant on a real scale. With a stronger spring or with a larger barrel and the differences in the solutions could mean the difference between minutes or hours between windings, making the Preisendorfer solution more complete with relatively little effort. Ultimately, including the two extra terms in the deviation increases the accuracy of the solution but only slightly, and the effective difference is negligible, However, calculating the difference between the solutions and analyzing them helps the designer determine how accurate of a solution is required and helps in understanding the variables that affect the fusee mechanism.

This concludes the analysis of the fusee mechanism design. The fusee profile data can be found in the digital library referenced in the appendix. To make the results available for manufacturing, the TK Solver 5.0 was linked to an Excel program, seen in Figure 39. A parallel example by Ian Glasgow used the data from this analysis to parametrically model the fusee in Solidworks (Figure 40) and generate G-code for a Hass CNC Lathe [7].

preisendorfergs lyre clock app.tkw			
Inputs			
Variable	**Value**	**Unit**	**Description**
#threads	19.125		number of threads on fusee
R	1.1875		radius of Barrel (in)
T	3		torque to run clock (lb-in)
K	0.1428		spring constant (lb/radian)
p	0.01326		pitch of fusee
r_o	0.9375		beginning radius of fusee (in)
#incra	100		must be + integer
Wire Diameter	0.05	inches	
Fusee Length	1.59375	inches	
Treads per inch	12		
Finish Pass Depth of Cut	0.005		
Retreat Distance (X)	0.1		
Program Number	301		
Revolutions Per min	100	rev/min	Spindle Speed

Outputs			
Variable	**Value**	**Unit**	**Description**
Thread θ	103.67256		total fusee angle in radians
dθ	0.1036726		differentail theta length for 1000 increments

Figure 39: Excel to TK Solver dashboard

Figure 40: Modeled fusee

Chapter 6: Discussion and Conclusion

The pursuit of excellence reaches many areas. The University of Idaho began the pursuit of excellence on another path when it developed the *Solid Modeling, Simulation and Manufacturing Capstone* course for students. The challenge of adding more and more content while maintaining the quality of student learning is something that university has become adept at facing. Student scores and pass rates have maintained through the reduction of time spent on the relevant material and as a result of the condensed schedule, scores have increased dramatically on the CSWPA Surfacing and CSWE exams. The material added to the course has data supporting its effectiveness at teaching students to the quality of a Certified Solidworks Instructor while also providing a deeper understanding of both how the material is relevant and why information is presented the way it is within the Solidworks interface.

When applying Solidworks to real world problems, the program can be used as a design and a research tool. Solidworks can be used to calculate values like an objects moment of inertia that must be analyzed outside the software and then also generate models that require math that Solidworks cannot complete itself. In the case of the dynamic analysis of the Strutt Epicyclic Train Clock, the initial design presented by Smith was able to be modeled and analyzed using the moments of inertia of the gear train to find the torque requirement of the spring. Once the minimum torque required for the clock to rotate is found, the value can be inserted into the equation for the profile of the fusee and be remodeled in Solidworks based on the new profile. This would inherently create an iterative design process to increase the efficiency of the clock that would require the input of an engineer or designer through every step. This data can then be shared among the community to help others design their fusee mechanisms and provide an example of how a clock can be optimized for a less powerful spring.

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Appendix

The relevant data, programs, and instructional material for this thesis can be found in an online data library located on the University of Idaho Mechanical Engineering department's shared drive in the file location seen below:

S:Storage-Engineering>Documents>Senior Design>-Course Folders>ME 490>Ryan Gonzalez Thesis

The ME 490 content area is broken down by semester and then exam with assignment subfolders and relevant exam documents included with each exam. Relevant class documents include video content, shortcut setup guides, and remote setup guides. Exam content folders include homework assignments, video examples, any included quizzes or in-class examples, and extra relevant material like gauge tables or weldment profiles.