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The Application of Small Batch Sizes to the Design and Delivery of Engineering Courses

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The Application of Small Batch Sizes to the Design and Delivery of Engineering Courses

Introduction

Many of the current best practices in education have parallels in lean manufacturing strategies. This suggests that lean practices can be used as a framework for the design and delivery of engineering courses. The purpose of this paper is to provide ideas for implementing lean methods in the educational process. The specific focus is on the lean concept of using small batch size to improve production and quality in engineering education.

Small batch production provides several benefits in a manufacturing process. These include shortening time to final product, enhanced quality, and increased product flexibility [1]. This paper examines how similar benefits can be obtained by applying small batch ideas to education.

A central premise of this paper is that the introduction of lean principles creates a framework in which to implement best practices in education. The small batch design supports a variety of educational best practices. These include providing rapid feedback to students [2] – [4], which can be used to improve performance [5] by giving students a chance to correct and learn from errors [6]. Small batches also reduce cognitive load by dividing course material into manageable chunks [7] - [17].

A number of authors have recognized the relationship between lean practices and best practices in education [18] – [24]. These range from the implementation of general lean ideas (such as reducing waste) [18] – [20] to the application of specific lean strategies such as six-sigma [21] - [23] and 5S [24]. None of these authors, however, specifically address the use of small batch size concepts to enhance the educational practice.

The following sections develop the application of small batch ideas to the design and delivery of engineering courses. The principles of small batch size in a manufacturing environment are presented first to define terms and concepts. These are then imposed on a common course structure to examine potential differences between "large batch" and "small batch" course design. A third section presents a variety of strategies and tools that can be used to facilitate small batch course design.

Principles of Small Batch Size

A logical starting point for examining the effects of batch size in a teaching environment is to first introduce the concept of batch size as it pertains to manufacturing. We can use the following definitions:

- *Batch* – A group of products that are manufactured simultaneously.
- *Transfer batch* – A group of products that are transferred from one operation to another as a group. A transfer batch is a subset of a batch.

As an example[1] of how batches work in manufacturing, consider Fig. 1. Assume that we have two products, X, and Y. Both products have to be processed in the same plant at the same stations, A, B, and C. The stations have the following capabilities:

- Station A – Can process 1000 units of X per day and 2000 units of Y per day.
- Station B – Can process 2000 units of X per day and 2000 units of Y per day.
- Station C – Can process 1000 units of X per day and 2000 units of Y per day.

Suppose we have a production order of 8000 units each of X and Y with the need to deliver X first. In a "large batch" process, we would process all of X first and then process all of Y. The timeline for the large batch process is shown in Fig. 1. Station A takes 8 days to process the batch of 8000 units of X. These are then transferred to station B, which takes 4 days to process the X batch. Then station C takes 8 more days to process X and the complete batch of 8000 units is shipped after 20 days.

Product Y follows in another single batch of 8000 units. Station A starts processing Y on the ninth day (after X has finished) and completes 8000 units in 4 days. These are transferred to station B, which takes another 4 days to process the batch of Y. These are transferred to station C where they have to wait 4 days for X to finish processing. After the wait, station C takes 4 days to process Y, and the batch of 8000 Y units is shipped after 24 days.

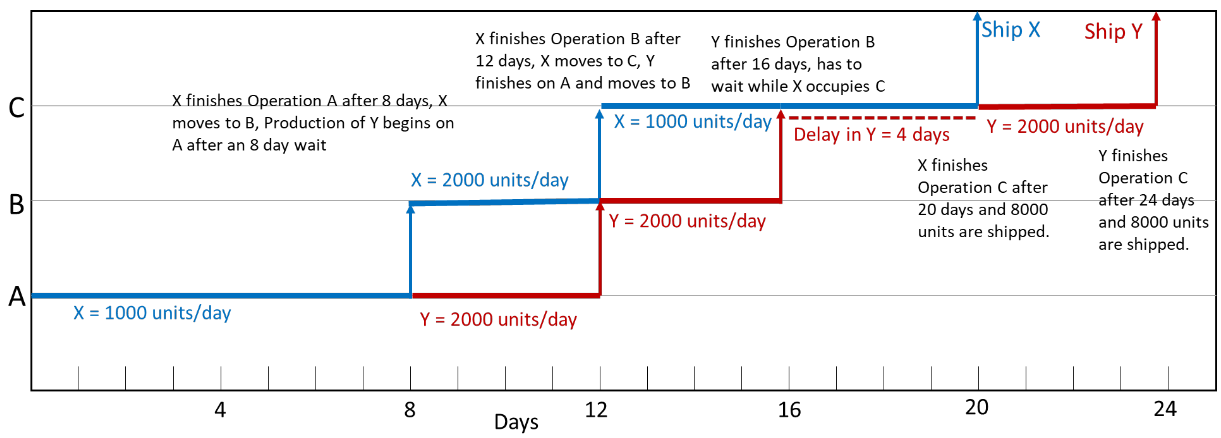

Figure 1: Large batch operation sequence.

The theory of small batch processing says that we can do better than the above. As an example, consider Fig. 2. In Fig. 2, we are going to break both X and Y into batch sizes of 4000 units, and use a transfer batch size of 2000 units (after we finishing processing 2000 units, we transfer it to the next station to start processing).

With the small batches, we now spend 2 days processing the first transfer batch of X at Station A. This moves to station B for 1 day, and station C for 2 days. The first transfer batch is fully processed in 5 days. The second transfer batch follows with a two day lag and is fully processed after the 7th day. The first batch of 4000 units of X ships after the 7th day.

[1] Example adapted from Nicholas [1].

We follow this with a small batch of Y. It takes one day to process a transfer batch of Y on each of station A, B, and C. Including a wait for X on station C, the first transfer batch of Y finishes processing on the 8th day, and the complete batch of 4000 units of Y is ready to ship after the 9th day. The second batches of X and Y follow these and all 8000 units of X are shipped at the 13th day and all of Y is shipped by the 15th day (compare to Fig. 1 where it took 20 days to ship all of X and 24 days to ship all of Y!).

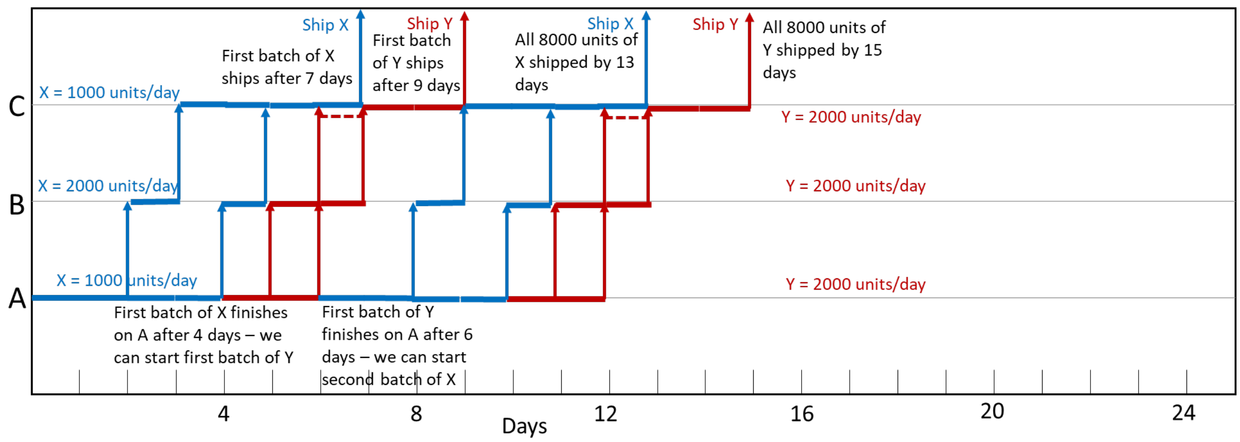

Figure 2: Batch Size Reduction Reduces Production Time.

The above highlights the advantages of small batch production as they pertain to production time. Small batches also have the following advantages:

- Improved efficiency – Shorter time to product delivery and better utilization of equipment.
- Improved quality – Defects are detected sooner. Defects can be repaired in the current batch and do not propagate to subsequent batches.
- Flexibility – If we have a new "rush" order come in (say for product Z), we can insert Z between the smaller batches rather than waiting to finish a large batch.

The above is a very cursory introduction to the theory and benefits of small batch production in a manufacturing context. This is, however, sufficient to allow us to examine the benefits of small batch theory in an educational setting.

Using Small Batch Sizes in Education

The above principles of small batches are readily adaptable to the teaching process. This section looks at the overall principles of small batch education while the next section presents specific ideas of how to implement small batch thinking.

The effect of batch size on course delivery is demonstrated using two idealized course structures. The first is a "large batch" course modeled on common practices in course design. The second, "small batch", course follows the same flow of the large batch course but uses small batch delivery to improve the efficiency, quality, and flexibility of the course offering.

The Large Batch Course

Figure 3 shows the layout of a large batch course that is based upon the following assumptions:

1. The course is a 15-week course with 3 meetings per week.
2. The course is divided into two primary modules that each span 6 weeks of the course.
3. Each module has three submodules that span two weeks of the course.
4. "Processing Stations" are course items and include:
   a. Information delivery. In most courses this is the class meeting time commonly used to deliver a lecture. Information is delivered in a "weekly batch".
   b. Homework. Homework is assigned at the end of each "information batch" and due at the end of the subsequent week.
   c. Homework grading: Homework grading is completed within a week after the homework is collected.
   d. Project work: Engineering courses commonly contain projects to tie together topics. In our model, each module has a culminating project that is assigned at the completion of module information delivery. The project has the following processing times:
      i. A project duration of three weeks.
      ii. Grading time is one-third of the project length (i.e. one week).
   e. Exams: The instructor has a choice of giving either a "topical module exam" (based solely on course information and homework), or a "comprehensive module exam" (that also includes ideas from the project work). In order to allow students adequate time to process feedback, the following rules apply:
      i. A topical exam cannot be given until the second course day after all homework has been graded and returned.
      ii. A comprehensive module exam cannot be given until the second course day after all project work has been graded and returned.

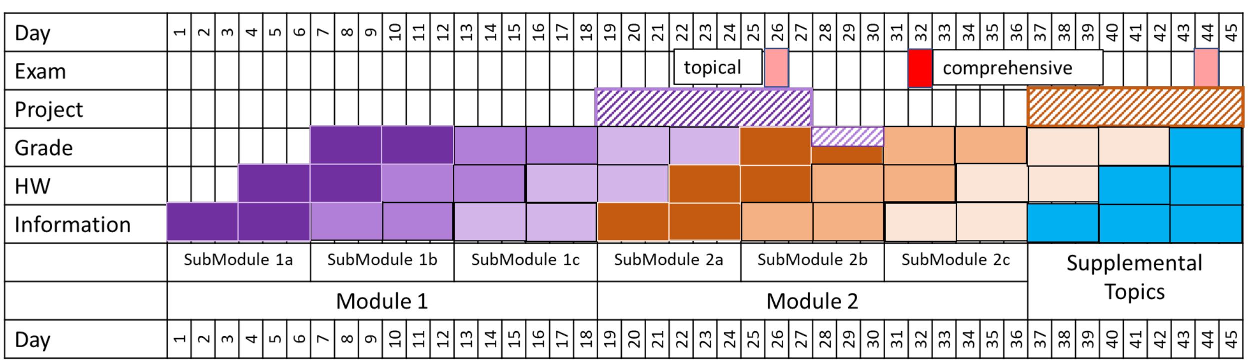

Figure 3: Flow of work in a "Large Batch" engineering course.

Using the idealized model described above, the flow of work through the large batch course is shown in Fig. 3. The first three days of the course are used for information delivery. Homework is then assigned and completed through days 4-6 of the course. The homework is submitted on day 6, graded and returned on day 9. This pattern repeats itself each week.

At the end of the information delivery for the module (day 18), a comprehensive module project is assigned. With a 3-week duration, the project is submitted on day 27 of the course, graded, and returned on day 30 of the course.

If the instructor wishes to administer a topical module exam, the exam can be given on day 26 of the course. A more comprehensive module exam cannot be given until day 32 of the course.

A similar process runs for the second module, where information delivery begins on day 19. Note that even though information delivery ends on day 36, we run into the following limits:

1) Project 2 ends on the last day of the course – day 45. Grading of the project runs into finals week with no chance for students to see project feedback.
2) A topical exam for module 2 can be given on day 44, but no comprehensive exam can be given based on the defined rules.
3) Additional topics can be introduced on days 37-45, but students will only receive homework feedback for topics assigned on days 37-39. Grading of other homework carries over into finals week.
4) If the instructor gives a topical exam on day 44, the instructor has to grade the topical exam, project 2, day 40-42 homework, and a final exam before the grading deadline.

The above "large batch" model is fairly representative of many engineering courses. This model reveals several challenges for both faculty and students. These include:

1) Students are relatively idle in the first week. After this, they have only homework to complete during days 4-18.
2) The model does not allow students time to fully engage topics from days 40-45. As such, the information delivered in these days has diminished value.
3) If the instructor uses a topical exam, this falls in the same week that the projects are due which produces a spike in student workload.
4) The instructor can smoothen student workload by giving a comprehensive module exam, but the course does not contain enough time to give such an exam for module 2.
5) The instructor will experience workload spikes on days 28-30 (with a topical exam), and during finals week.

In manufacturing, we improve upon the large batch model by moving to smaller batches. The next subsection examines a small batch model for the same course presented above.

The Small Batch Course

The small batch course is built upon assumptions similar to the large batch model. The first three assumptions are identical to the large batch model:

1. The course is a 15-week course with 3 meetings per week.
2. The course is divided into two primary modules that each span 6 weeks of the course.
3. Each module has three submodules that span two weeks of the course.

The fourth assumption defines the difference between the large and small batch designs. The small batch course implements the following rules, as illustrated in Fig. 4:

4. The small batch contains the same set of processes, but divided into smaller batches:
   a. Information delivery. Information is delivered in a daily batch..
   b. Homework. Homework is assigned at the end of each information batch and due the next class day.
   c. Homework grading: Graded homework is returned the class day after the homework is collected.
   d. Project work: A small batch model divides projects into parts. Part 1 of the project applies concepts from submodule 1. Part 2 builds on the results of Part 1 by adding concepts from submodule 2. Part 3 finishes the project by adding concepts from submodule 3. Each part of the project can be assigned at the end of information delivery for the current submodule:
      i. The above means projects begin at the end of the first submodule.
      ii. Students are given one week to complete each part of the project.
      iii. Grading time for each part of a project is assumed to be one-third of the length of the part (in this case that means one class day).
   e. Exams: Exam rules for the small batch model are the same as for the large batch model (Note: A small batch model suggests exams at the end of each submodule. This is not implemented here to allow for a more direct comparison to the large batch model).

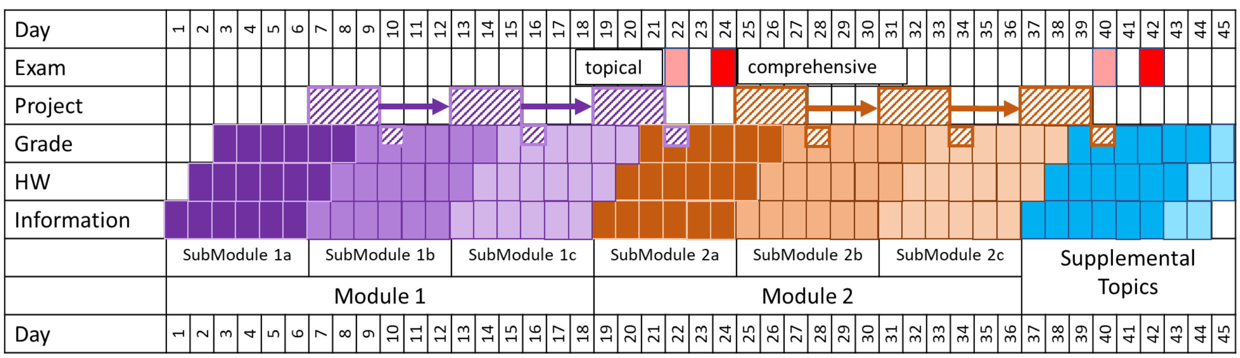

Figure 4: Flow of work in a "Small Batch" engineering course.

The flow of work through the small batch course is shown in Fig. 4. Information delivery starts on day one and a daily homework set is assigned. Homework is submitted on day 2, graded and returned on day 3. This pattern repeats itself each class day.

At the end of the information delivery for the first submodule (day 6), part 1 of the module project is assigned. This is completed on day 9, graded and returned on day 10. The project has a “delay” of two class days which allows students to address and repair defects in part 1 of their submission prior to starting part 2 of the module project. This is a characteristic of small batch production where the small batch size allows for the correction of defects so the defects are not passed along to the next batch. The full module project is completed on day 21, graded and returned to students on day 22. At this point, we are on the same information delivery pace as the large batch model, but 8 class days ahead in providing feedback on student work.

If the instructor wishes to administer a topical module exam, the exam can be given on day 22 of the course. A more comprehensive module exam can be given on day 24 of the course.

A similar process runs for the second module, where information delivery begins on day 19. An important characteristic of the small batch model is that we no longer run into the end-of-semester limits created by the large batch model. Some key differences include:

1) Project 2 ends on day 39 with students receiving feedback on day 40.
2) Either a topical exam (day 40) or comprehensive exam (day 42) can be given for module 2.
3) Students receive feedback on work for additional topics introduced on days 37-43.
4) All coursework is graded by day 45 so the instructor has no extra grading burden heading into finals week.

The "small batch" model covers the same content as the large batch model, but produces the following advantages for faculty and students:

1) Students are working from the first day of class. This smooths out the student workload.
2) Project work is better distributed to minimize spikes in student workload.
3) Students have time to correct flaws in projects before moving to the next part of the project. This improves their learning and makes grading easier since the instructor does not have to follow the effects of one error through the whole project.
4) The course has 4 additional "useful" days at the end of the semester. The course information maintains full value through day 43.
5) The instructor has greater flexibility to give either a topical or comprehensive exam at the end of each module.
6) The instructor workload is relatively level throughout the course and into finals week.

In manufacturing, small batches improve efficiency, quality, and flexibility. We see these same gains in a small batch model for engineering courses in the following ways:

- Improved efficiency – Shorter time to provide feedback to students. Better distribution of both student and faculty workloads.
- Improved quality – Daily feedback on homework allows errors and misconceptions to be addressed early. Feedback on project parts provides time to correct defects and prevent them from propagating throughout the project work.
- Flexibility – The course "gains" 4 useful days at the end of the semester. If desired, these days can be distributed throughout the semester to allow for review, revisiting difficult topics, or as open workdays.

Several examples of the above gains include the following results:

1) Prior to moving to small batches, project grades in a Machine Design Course typically ranged from 75% to 85%. After moving to a small batch model, project grades in the same course improved to a typical range of 85% to 95%.
2) The author has been able to move from a "finals week grading frenzy" to a finals week that is devoted solely to delivering and grading a final exam.

The small batch model also has several challenges in its implementation. In manufacturing, the theoretical optimum batch size is a single unit. However, this assumes zero cost of handling the part and moving from station to station. As such, the optimal batch size is determined by a combination of the processing and handling time. This results in the following areas of caution:

1) The workload is more distributed so students have the advantage of fewer spikes in work. The downside is that students can feel the workload is relentless. As such, the author typically uses the "extra" days at the end of the course to distribute workdays through the semester to provide breaks in the workload.
2) The author has applied the small batch model to exams and found a disproportionate increase in handling costs. The emphasis that students place on quizzes and exams appears to reduce their compatibility with the small batch models run by the author.

The small batch model for course design has been shown to be an effective course structure. A variety of methods and tools exist to assist the instructor in the implementation of a small batch course design. The next section briefly outlines some of the tools and assignments that the author has used in small batch teaching.

Tools for Small Batch Course Design

The previous section demonstrates how small batches improve the coordination of information delivery with student assessment and grading. This section provides a number of examples of how to divide larger work into small batches. The strategies presented are not meant to be comprehensive, but rather to serve as a catalyst for readers to either adopt, or develop ideas of their own.

This section provides examples of small batch delivery for:

- Information delivery – Considering both lectures and on-line methods.
- Homework – How to move to daily homework.
- Project Work – Building multipart projects.

The above are selected as being representative of common engineering assessments. The goal of this section is to demonstrate that most aspects of an engineering course can be broken down into small batches.

Information Delivery

"Information delivery" is what we might commonly think of as the lecture. The advent of formats such as the flipped classroom, on-line classes, and hybrid classes requires us to lump these together under the more generic name of "information delivery".

The small batch format of information delivery requires the information to be broken into well-defined chunks that include a definite start, end, and learning objective. Part of the challenge of small batch delivery is placing information into a "package" that is small enough for a student to process. In spite of the fact that a common lecture period is 50-60 minutes long, the authors typically target a maximum of 20 minutes of information delivery for a given class period. This can include delivery of the basic information (theory, equations, and the like) and working through one or two quick examples. The information has to be well structured to ensure it is contained within the short time frame. While some instructors may object that this removes the opportunity to "expand on concepts", the reality is that students learn better when material is straight to the point with minimal embellishment [16], [25]. The remainder of class time can then be used in an active learning format as students engage the information by working on the daily assignment. This is a critical part of the small batch production as this time is where the quality of the information delivery is assessed, defects are repaired (clearing up misconceptions or weak understanding), and students are prepared to move to the next batch of information delivery.

Homework

Homework is closely tied to the information delivery in a small batch course structure. The instructor does not want to wait to assess the effectiveness of the information presentation, so daily homework represents a method to identify and correct defects in student understanding as a real-time process. While students might not fully complete a homework assignment during the class time described above, they should at least get to the point where they understand the necessary process to solve the homework.

Homework grading is a second essential part of the small batch process. Students should have feedback by the start of the next class day. One ideal way to do this in many engineering courses is to automate the homework. This can be done using electronic homework resources provided by a textbook company, or instructor-developed resources posted to the learning management system (LMS) for the course. A good format for homework is the use of problems where the numbers in the problem are randomly generated (within specified ranges) and students get solution feedback on each attempt (such as the correct solution for the current values). When students have multiple attempts at this type of problem they have a chance to locate and correct their own defects. This completes the small batch cycle of "information delivery – practice – evaluate" allowing students to move to the next class day and a new batch of information.

Project Work

Projects are typically used to tie together various course elements to provide students with a more comprehensive perspective of how the elements interact with one another. The scale of a project can range from a relatively small project that spans 2-3 weeks, up to something such as a capstone design project that might span 2 semesters. Here we will outline the small batch process by considering a mid-sized project that might span 3-6 weeks of a course.

The course structures outlined in Figures 3 and 4 show a course that uses "module projects" to summarize topics from a given course module. In the large batch structure, the project begins at the end of the module when students have all the information needed to complete the project. In the small batch structure, projects are created in a sequential manner. The small batch project sequence is designed so that the projects can be implemented in piecewise fashion as the instructor proceeds through the course information related to the project. The integration of project topics is achieved by building each phase of the project upon the solution of the previous phase. Some key elements that the authors use to support a small batch course structure include:

- Cover page submissions – Each part of the project is collected as a set of student calculations attached to a cover page (see appendix A for a sample cover page). The cover page allows the instructor to quickly evaluate critical results and provide feedback within one or two class days after the submission.
- Ability to correct previous parts – The use of multi-part projects introduces the opportunity for students to receive mid-project feedback and make corrections before continuing to the next part of the project. This ability ensures that defects are corrected before the project proceeds.
- Final reporting – If a cover page is used to evaluate all parts of the project, the submission of the last cover page serves as a check to verify the students have properly calculated the results. Quite often, a final submission is useful to be sure the elements of the project are tied together. The small batch approach suggests these should be concise presentations rather than a multi-page report. A more concise format often requires better writing quality from students, shortens grading time, and allows time for revisions to correct defects. Several examples of final reports that the authors have used include:
  - Memo report – Describe the project and results in a single page.
  - Portfolio report – Describe the project in a single page with the intent of creating the page in a way that would impress a prospective employer [see Appendix B].
  - A3 report – Use a standard A3 format [1] to describe the project and results.

The above approach to project reporting allows the students to receive continuous feedback on their project, and correct defects as they proceed, while also allowing for quick grading.

Conclusions

The use of small batch principles can provide significant benefits to both instructors and students. Small batches allow instructors to make better use of time throughout an academic term by allowing for smoother work flow and timely feedback.

From a student perspective, the small batches provide an even distribution of work, and ensure that proper feedback is received before continuing with course material. The instructor also benefits from a more even workload and the ability to assess and correct defects in student understanding as they happen.

A primary purpose of this paper has been to demonstrate that the principle of small batch production applies equally as well to the education process as it does to the manufacturing process. The paper has demonstrated that small batch courses have a more efficient delivery of course information and assessments, and that the increased efficiency produces effects that are consistent with good educational practice. These effects include rapid feedback, chances for students to correct and improve their work, and a consistent work load.

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Appendix A − Sample Cover Page for a Project Part

MME 342 – Module 1 Comprehensive Project
Static Stress Analysis and Design with FEA Verification
Cover Page - Part 2 – Bicycle Crank Analysis

Grading: 20 points total. All points are based on unsatisfactory/satisfactory scale with no partial credit.

Table 1: Part 1 Values - Enter (type) the indicated values from Part 1 of the project in the table below. Use values from your "Standard Mesh" model. **Be sure to include units. Limit values to 3 significant figures**. (5 pts)

	Point A	**Point B**
Von Mises Stress		
Principal Stress, σ_1		
Principal Stress, σ_3		
Calculate the Max Shear Stress $\left(\tau_{max} = \frac{(\sigma_1 - \sigma_3)}{2}\right)$		
Deflection at Point C		

Table 2: Part 2 Values - Enter your hand-calculated values from part 2. Be sure to include units. Limit values to 3 significant figures. (5 pts)

	Point A	**Point B**
Von Mises Stress		
Principal Stress, σ_1		
Principal Stress, σ_3		
Calculate the Max Shear Stress $\left(\tau_{max} = \frac{(\sigma_1 - \sigma_3)}{2}\right)$		
Deflection at Point C		

Table 3: Comparison - Calculate the percent difference between the values in tables 1 and 2 above. Enter the percent difference in the table below. (5 pts)

	Point A	**Point B**
Von Mises Stress		
Principal Stress, σ_1		
Principal Stress, σ_3		
Max Shear Stress		
Deflection at Point C		

Comment: (50 – 100 words) Explain why, or why not, the percent difference values in Table 3 demonstrate good agreement between the FEA model and the hand calculations (5 pts – comments need to show more refection than "*results are within acceptable % difference*"):

Submit the following:

1) **This Cover Page document (Values filled in and comment included) with attachments as a single Word document.** *I will only open the cover page document, so if the required attachments are not in that file, you will receive no credit*.
2) The cover page attachments will be a neatly documented set of all calculations. These can be handwritten or MathCad. In either case, be sure to include words to describe what is being calculated. Calculations that include only equations with no description of the calculation being performed will not receive credit.

Appendix B: Sample "Portfolio" summary report for a course project

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Planar Manipulator[2]

Problem Definition: Design and build a planar mechanism that traces a set path.

Design Approach:

1. Designed five-bar linkage with two stepper motors in SOLIDWORKS and 3D printed the links.
2. Assembled the physical mechanism.
3. Sketched shape of MN in SOLIDWORKS and performed motion study to generate position data (see Fig. 1).
4. Transferred position data to Arduino code to move mechanism in desired path (see Fig. 2).

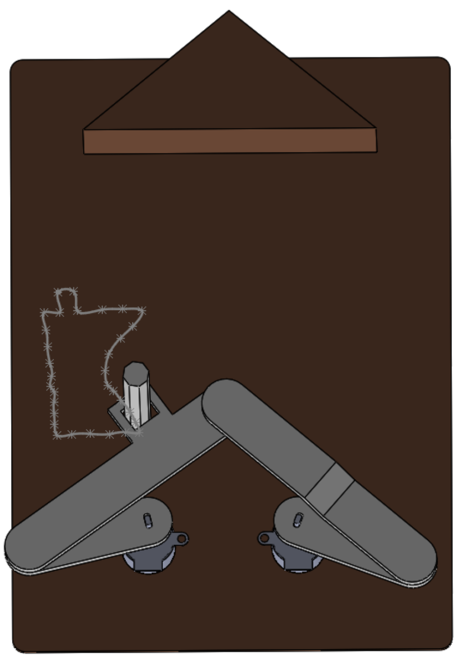

Figure 1: SOLIDWORKS mechanism with sketched path

Innovations:

The following non-required features were added.

1. Joystick Module: Added to system to allow manual control of motors. This allows user to easily move mechanism to starting position.
2. RFID Authorization: Added for system security. System cannot be manipulated before scanning the RFID tag.
3. Button: When the button is pushed, the mechanism moves around the path. The joystick is locked while the mechanism is tracing the path.

Results:

1. Mechanism followed path with good repeatability.
2. Add-on features worked as expected.
3. Mechanism vibrated back and forth throughout path, resulting in imperfect lines. Suspected this was due to timing difference in steps of motors.

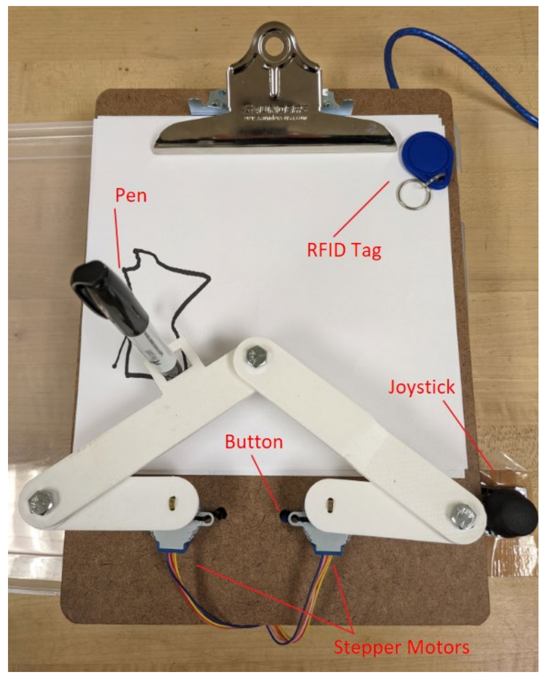

Figure 2: Physical mechanism with traced path

Challenges:

1. The joystick moves up/down/left/right, but the motors move clockwise and counterclockwise. Testing was performed to determine the most natural pairing of joystick movement to motor rotation.
2. The original Arduino code for RFID authorization allowed any RFID card to unlock the system. Additional lines of code were added to recognize the ID number specific to the tag shown in Fig. 2.

[2] Contributed by H. Loukusa