Engineering Educators Bringing the World Together
2025 ASEE Annual Conference & Exposition
Palais des congrès de Montréal, Montréal, QC • June 22–25, 2025
Paper ID #49418

Game-Based Learning in a Manufacturing Setting to Teach Statistical Process Control

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Abstract

Advanced manufacturing firms wishing to adopt new digital technologies need a workforce that has the skills to collect, interpret, and analyze data. Unfortunately, many promising students who have an aptitude for work in manufacturing struggle to overcome large gaps in their math education and are missing traditional math skills required to complete data analysis courses. Students who enroll in advanced manufacturing programs often fear a repeat of ineffective math instruction lacking context or application. Game-based learning provides an opportunity to change this mindset. During standard instruction, if students cannot solve a math problem quickly, they are inclined to believe their capacity to learn data skills is inadequate and fixed in place. Simulations and digital games can directly link data skills to applications in manufacturing to solve problems on the factory floor. In games, failing before achieving a goal is not only an inherent part of the experience, but can be rewarding and satisfying. The most effective educational games are carefully scaffolded to include a combination of conceptual, procedural, and declarative knowledge development, which encourages students to move from concrete examples to generalizations and abstractions. In contrast to stand-alone math courses in data analysis and statistics, data skills integrated through a factory-floor narrative can better prepare students to transfer their knowledge to authentic manufacturing contexts.

In this work, we created simulations and learning games to help disaffected technicians and undergraduate students solve data analysis problems in the context of manufacturing. These simulations and games were integrated into a targeted series of introductory data-for-manufacturing modules. The first learning module uses a digital web/mobile game to introduce statistical process control (SPC) in a digital manufacturing environment. Over the course of four weeks, players learn to operate injection molding machines, fulfill increasingly larger orders for high-quality injection molded parts, apply SPC methods and tools to meet in-game challenges, and improve the efficiency and productivity of their manufacturing process. In between play sessions, students are provided with online learning videos, math exercises, and in-person instructor-led lab activities which are grounded in the context of the injection molding SPC game.

1. Introduction

1.1. Manufacturing Workforce Training Needs

Companies that aspire to improve manufacturing process control and adopt new technologies need a workforce that can interpret and analyze data. While shop floors are rich with opportunities to improve processes, systems, and product design, manufacturing technicians are often unable to identify these opportunities because of their poor applied math skills. The global consulting firm Deloitte highlights data analysis, automated process control, and statistical analysis as crucial skills for the emerging manufacturing workforce [1], [2]. However, many adult learners are anxious about their math skills and struggle to overcome large gaps in their math education. According to federal data from the 2020 NPSAS, 50% of Black students, 45% of Hispanic or Latino students, and 40% of all students at 2-year institutions reported having taken remedial or developmental education courses [3]. A Columbia University study of 250,000 community college students found that of students who were referred to developmental education for math, only 33% completed a remedial math sequence, with only 20% passing the relevant entry-level math course within three years [4]. Low retention is a primary challenge for community colleges, with only 39.2% of full or part-time students enrolled in 2012 earning a credential from either a two or four year school within six years of initial enrollment [4], [5]. In addition, colleges and universities are providing increasingly more (and demonstrably subpar) fully online math instruction [6]. Students see standard remedial math content as disconnected from real-world applications, and this is a major hurdle for workforce education programs in advanced manufacturing [7]. Many government policies such as AB705 in California, USA are essentially eliminating remedial classes from higher education. This void in math instruction represents an intimidating barrier for students pursuing careers in manufacturing and other STEM fields. Workforce training solutions need to be interactive, engaging, and scalable to prepare students in math and data analysis skills to fill advanced manufacturing jobs.

1.2. Digital Simulations and Game-Based Learning in Manufacturing Workforce Training

There are a wide variety of digital simulations used for training the manufacturing workforce. Standard desktop procedural training simulations can be highly effective when integrated into online courses [8]. Immersive virtual reality experiences can support psychomotor skills acquisition [9], [10]. Augmented reality and game-based learning interventions can significantly increase students' intrinsic motivation [11] and support learning of engineering analysis [12]. Digital twins have a large potential for workforce training at scale, giving students access to real-time data and allowing them to train on state-of-the-art equipment [13]. Manufacturing games have also been used to teach a variety of high-level topics in manufacturing such as life-cycle assessment [14], supply chain and systems thinking [15], lean manufacturing [16], exploration of commercial applications of advanced manufacturing [17], training games customized for specific manufacturing companies [18], and many more. However, few workforce training simulations or games focus on bringing statistics or applied math to a shop floor setting.

1.3. Mathematics Education Using Game-Based Learning

Multiple meta-analyses have shown that playing STEM games leads to significant increases in academic performance when compared with traditional instruction based on both measured learning outcomes and increased student motivation [19], [20]. Progressing through a simulation or game can quickly build confidence in math and other STEM skills. Many players will methodically explore the rules of their environment, get feedback from the game, and try different approaches [21]. The most effective math games are carefully scaffolded to include a combination of conceptual, procedural, and declarative knowledge development, which encourages students to move from concrete examples to generalizations and abstractions [20], [22]. In the same way young children use physical objects for early number counting, manipulating virtual mathematical objects and dynamic mathematical systems can help adult learners master new concepts [23]. According to Moyer-Packenham and Westenskow, the affordances of “virtual manipulatives” in digital math environments lead students to focus their attention on the constraints of each system, find creative solutions, and learn to transfer knowledge to different contexts [23]. Digital games and simulations that directly link math skills to manufacturing applications can highlight how mathematical thinking is necessary to solve problems on the factory floor.

1.4. Digital Tools to Teach Statistical Process Control (SPC)

Technicians and other incumbent workers in manufacturing face many math barriers (as described in Section 1.1) and there is an absence of scalable training materials focused on the real-world application of process control. For manufacturing workforce training programs, teaching statistical process control (SPC) in a classroom setting can be challenging. It is very difficult to design hands-on activities or manufacturing labs that allow students to observe large volume manufacturing that would demonstrate the principles of SPC. Moreover, even if students can observe high-volume manufacturing firsthand, they do not have the ability to engage in trial and error, make changes to the process, manipulate graphs in real time, or have visibility into the cause of variation. Standard classroom instruction on statistical process control is primarily geared to undergraduate and graduate students and assumes prerequisites in statistics and probability.

Digital tools can help to overcome these limitations. Previous efforts at creating digital simulations and games for SPC workforce training include digital environments that make use of darts or target metaphors [24], or dynamical displays of stochastic processes such as a digital Galton board as an analogy for manufacturing variation [25]. There is an opportunity to create digital environments that allow users to virtually operate equipment, gather and analyze data, interact directly with SPC tools like run charts and control charts, and better prepare students for on-the-job problem solving. In this work we leverage the advantages of digital environments to create a series of interactive simulations and games to teach statistical process control in a manufacturing environment.

2. Development of Process Control Interactive Simulations and Web Game

For this project, the goal of using interactive web simulations and game-based learning to teach process control is to gradually introduce data, charts, and statistics, linking the mathematics to a digital 3D manufacturing environment. We required dynamic data visualizations and an intuitive graphical user interface (GUI) for data manipulation to gradually introduce students to how process control tools (like run charts and control charts) are used in practice.

Figure 1 shows the simulation and learning game designed to teach statistical process control, where students operate an injection molding tool to manufacture plastic gears. Injection molding of plastic gears was selected as an appropriate and representative manufacturing process to teach statistical process control. Since most students in the program would be unfamiliar with the intricate details of injection molding, this choice is intended to focus their attention on data acquisition and statistical interpretation of the data. With injection molding, students should find it more difficult to attribute deterministic and random variation in manufacturing outputs to operator inexperience. Consistent fluctuations in temperature and humidity are easy to understand as sources of large variation in injection molding.

Figure 1. Interactive web simulation/game to teach statistical process control.

2.1. Simulation Tutorial Sequence and Instructional Design

A sequence of eight procedural training simulations were designed to be completed in the first four weeks of an online learning module as shown in Table 1. The weekly simulation objectives help familiarize students with the graphical user interface (GUI) and mechanics of the simulated manufacturing environment, and the first three weeks serve as a tutorial in preparation for the full game available in Week 4.

Learning Module Topic	Simulation Sequence
Week 1: Run Charts	S1: Introduction and injection molding error states
	S2: Run charts and process control basics
Week 2: Manufacturing Variation	S3: Histogram and normal distribution fit
	S4: Meeting large order with environmental factors
Week 3: Control Charts	S5: Basics of control charts and the $\bar{x}$ chart
	S6: Western Electric rules for control charts and quiz
	S7: Sampling plan
	S8: Overview of the S chart
Week 4: Process Capability	G: Full statistical process control game

Table 1. Overview of weekly content outline and corresponding simulation sequences and learning game in the first four weeks of the learning module on statistical process control.

In Week 1, simulation sequence S1 introduces the basic GUI elements and gives an overview of the injection molding process, input parameters, and error states, as shown in Figure 2. The first task for the user is to fix the tool by adjusting the main barrel temperature. In sequence S2 the user is then challenged to complete a customer order for 50 medium-precision gears, which motivates the introduction of run charts to measure the pitch diameter of the injection molded plastic gears. The user must account for the variability in shrinkage of the molded plastic parts to meet the customer design specs.

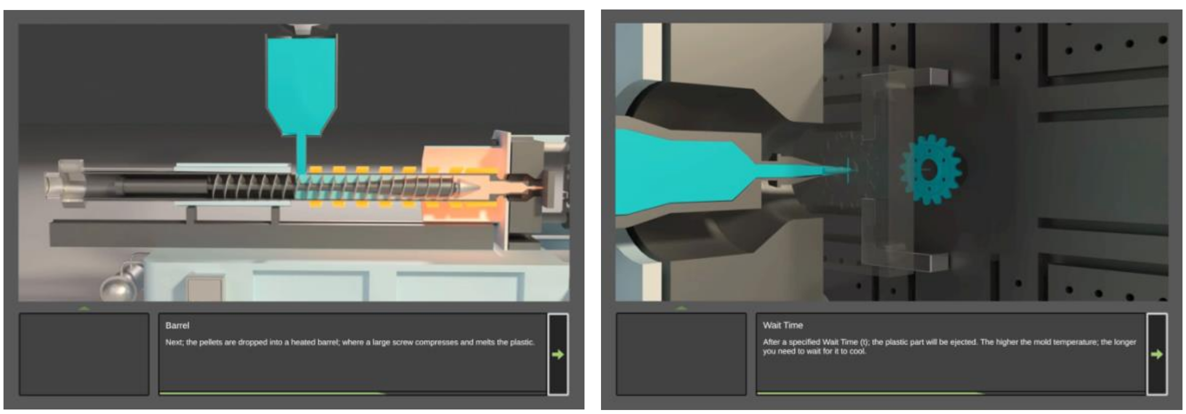

Figure 2. Screenshots of the simulation sequence tutorial S1, with visualizations of the injection molding process, input parameters, and error states.

The simulations in Week 2 introduce a histogram of the data and asks users to find the mean and standard deviation by manually fitting a normal distribution to the dataset using sliding bars. Users are then challenged to produce 200 gears, bringing their injection molding process back in control by sending their data to a "digital tool vendor" who guides them to interpret and their data and make tool adjustments.

Week 3 allows users to run their process, gather measurements in a run chart, manually fit the data (Figure 3), and dynamically build X-bar / $\bar{x}$ control charts (S5) and S charts (S8) for themselves. We introduce the four Western Electric rules for control charts and create a short interactive quiz in the simulation environment where users must correctly identify all Western Electric rule breaks in three randomized X-bar control chart datasets. Then, we motivate the need for a sampling plan through the narrative of a large time-sensitive order of 2,000 medium-quality gears, where the user cannot meet the order in time if they measure every single gear. The user must trust their process and continuously monitor their control charts to meet the order.

Finally, in Week 4 students can explore the open-ended game environment, given full access to the input controls and parameter space of the game. They must complete orders of increasing difficulty, managing tradeoffs, trying to get their process back in control, and fighting against the clock to complete orders on time. The intention is for the SPC game to replicate the feeling of being on a shop floor and test students' ability to apply their knowledge of how run charts and control charts are used in practice.

2.2. Design of the User Interface and Interactive Graphs

Early feedback on the learning module and beta testing of the simulation indicated control charts and the origin of control limits are an especially difficult topic for some students. We found the concept of calculating the "mean of means" or "average of the averages" is not intuitive. For this reason, we attempted to fully deconstruct the process of creating and using run/control charts. We designed a clear visual language for the graphs and other data visualization tools, and created an interactive GUI that allows students to experiment with data fitting and sampling.

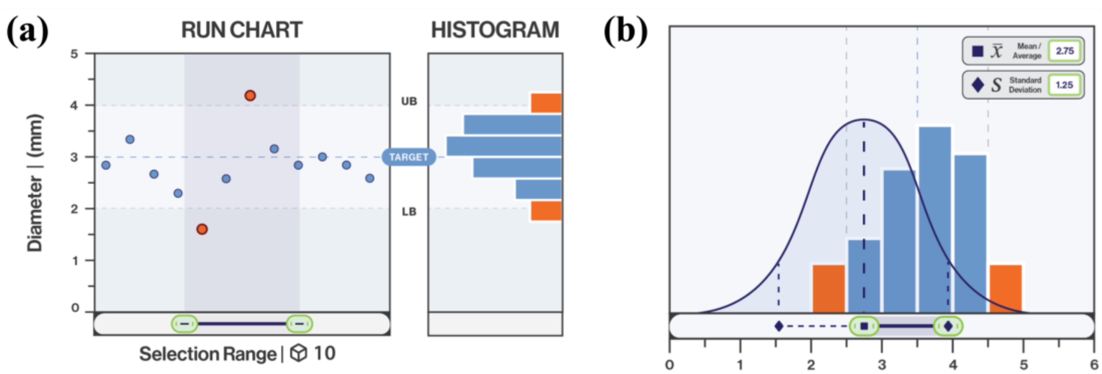

Figure 3. Design for interactive run charts and histograms which allow users to (a) select and bin run chart data in a histogram, and (b) fit a gaussian curve to histogram data.

As shown in Figure 3, the data in each run chart is color coded to indicate which measurements are in and out of spec for the current customer order. When the histogram is first introduced (Figure 3a) it is graphed vertically to line up with the y-axis of the run chart measurements. As data is dynamically added to the run chart, students can observe the count increasing in the appropriate histogram bin. Later in the tutorial simulation sequence the histogram is rotated (Figure 3b) and students are asked to interact with a normal distribution as a virtual manipulative, using sliding bars to fit a gaussian curve to the shape of the data. The symbols representing the mean ($\bar{x}$) and standard deviation (S) are dark blue squares and diamonds to make them visually distinct from the raw data in the run chart, and to indicate they represent a consolidation of information derived from multiple measurements. Further, to avoid confusion between run and control charts, the $\bar{x}$ and S data are plotted in the control charts shown in Figure 4 are distinct in color and formatting from the run charts in Figure 3.

2.3. Interactive Quiz on Western Electric Control Chart Rules

In Week 3 of the learning module the simulation training sequence S6 covers the Western Electric rules for control charts and culminates in an interactive quiz with randomly generated datasets. The quiz is delivered within the simulation GUI shown in Figure 4, allowing students to easily identify the exact location of rule breaks. This also allows students who are not ready for the quiz to return to a practice session where the computer assists them with identification of rule breaks in randomized datasets.

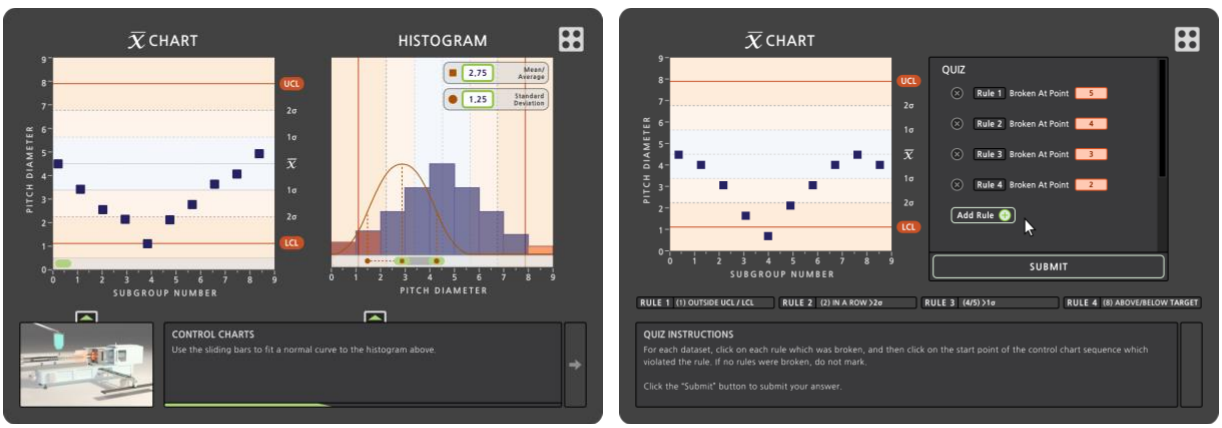

Figure 4. Interactive $\bar{x}$ control charts with control limits: (left) normal distribution fit of data binned in a histogram using sliding bars; (right) interactive quiz on Western Electric control rules.

2.4. Backend Model of Manufacturing Variation and Full SPC Game

As shown in Figure 5, the SPC simulations in Weeks 1-3 and the full game in Week 4 are built on a backend model that simulates manufacturing variation due to environmental changes. The backend model with three major error states of injection molding were included in the simulation: short shot (an unfilled part), flash (an overfilled part), and deformation of the plastic gears.

When the user finds an acceptable setting for the injection molding process, represented by the blue Error-Free Box in Figure 5, over time the target box will randomly shift locations, leading to worse outcomes which will break the W.E. rules. This requires constant shifting of temperature set points.

During early levels of the full SPC game, students begin by operating equipment that is well calibrated and easy to keep in control, and they receive orders for injection molded gears which can be easily produced. In the backend model the tool starts off with a large Error-Free Box that moves infrequently and in small steps. As the game increases in difficulty, increases in manufacturing variation are simulated by decreasing the size of the Error-Free Box and increasing the rate at which the box moves, changing the optimal parameter set points. This is meant to simulate more difficult environmental conditions or wear and tear on the tool.

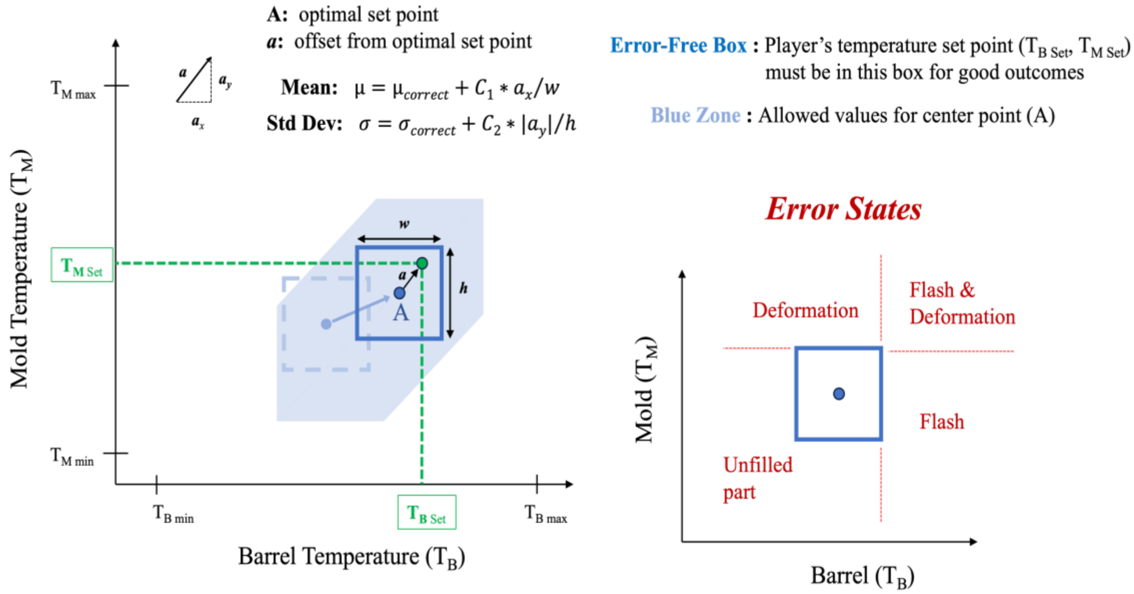

Figure 5. Backend physics model for the process control game.

3. Blended Learning Module on Statistical Process Control

The simulations and learning game were designed to be included in the first four weeks of an 8-week blended learning module on statistical process control, following best practices for blended learning [26]. Each week of the blended learning module contains 60-90 min of online learning content (short videos and concept check questions), 30 min of exercises using the interactive web simulations or the SPC learning game, and 3 hours of in-person hands-on labs.

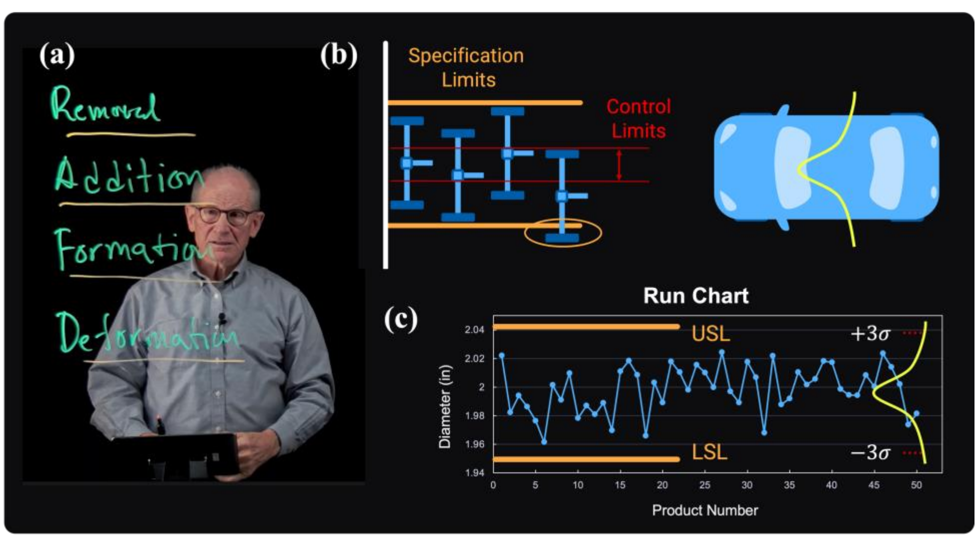

Figure 6. (a) Lightboard video instruction. (b) Slide figures using the analogy of parking a car to introduce specification limits, control limits, and process control. (c) Visualization of the ultimate goals of statistical process control in manufacturing.

3.1. Online Learning Videos and Concept Check Questions

Each week, a series of short 5-8 minute lectures introduce the student to key concepts in process control. The lectures were filmed using a lightboard setup (Figure 6a) where the lecturer is fully visible to the students and writes on a transparent whiteboard. All figures used in the videos use the same visual language as the simulation (e.g., run chart and control chart design) and provide a framework to introduce students to each of the topics in Table 1.

3.2. Integration of the Interactive Web Simulations and SPC Learning Game

The simulation sequences are interleaved among the videos and exercises of the module to help motivate and explain the online lecture content, providing an active learning break from passive viewing of videos in the online course and preparing students for the weekly labs. Each of the simulations and the learning game were integrated into the course in the following format: (i) students first watch a 3-5 minute video on a new topic relevant to the simulation, (ii) they are guided through a short simulation exercise where they apply the new information in a manufacturing environment to solve a problem, and (iii) they exit the simulation environment to watch a summary video which consolidates their new knowledge and provides more rigorous definitions or conceptual frameworks.

3.3. Hands-On Labs

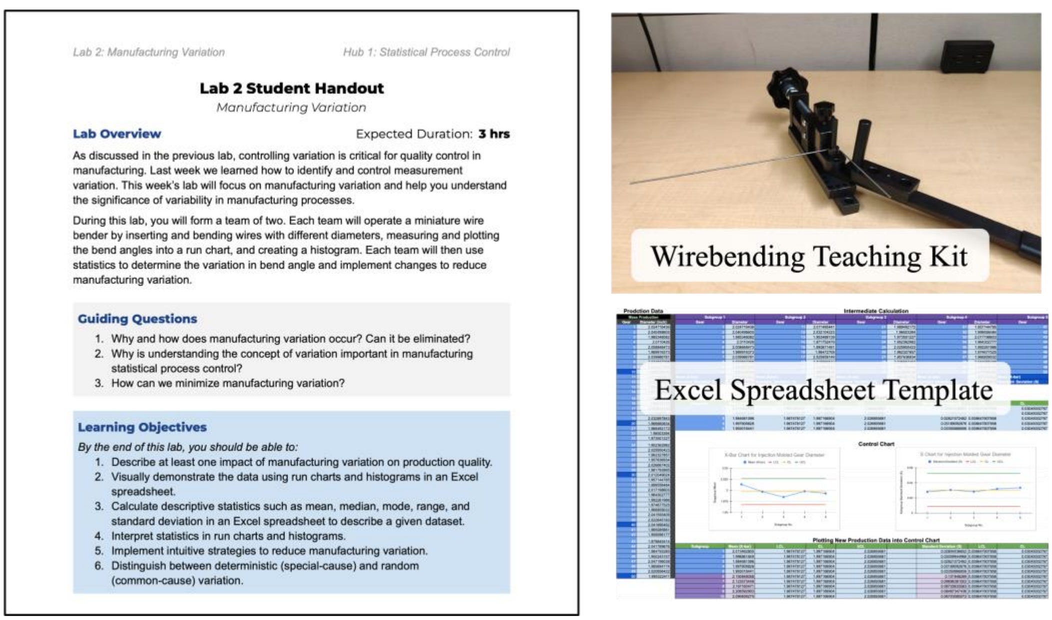

Figure 7. An example of the weekly hands-on lab activities using the *Kaka Industrial MUB-1 Mini Universal Bender* wirebending kit, designed to complement, consolidate, and expand upon the web simulation learning objectives.

After completing the 1-2 hours of online course content each week, students attend in-person labs facilitated by community college or university instructors. The three-hour hands-on lab exercises build on the learning objectives of the online videos, assessments, and simulation exercises. This is an opportunity for students to work with spreadsheet data in Excel or Google Sheets, and Figure 7 shows an example lab from the SPC learning module.

3.4. User Testing and Iterative Design of the Blended Learning Module

We conducted multiple rounds of feedback sessions and user testing with our target audiences of incumbent workers at regional manufacturing companies and undergraduate students. The iterative design process resulted in changes to the progression in the simulation sequence and learning game, updates to the GUI, and revisions to the module online learning content.

4. User Study and Summative Research Plans

4.1. User Study of Simulations with Undergraduate Students

To test the effectiveness of the simulation sequences for S1-S4 in isolation, the research team conducted a "think-aloud" user study to observe student behavior when engaging with the simulations, record and analyze their thought process, test the efficacy of the simulations, uncover student misconceptions, and make recommendations for improvement.

<u>Participants:</u> The assessment of the simulations was conducted with 8 undergraduate students, one sophomore, three juniors, and four seniors. All students were engaged in on-campus manufacturing internships in a variety of applications including additive manufacturing, metal casting, and industrial cybersecurity.

<u>Procedure:</u> After signing a consent to participate in the study, participants completed a pre-test using an identification number. They then heard a brief introduction to the simulation. Each was allocated approximately 40 minutes to complete the first four simulation sequences on a laptop and were asked to think aloud as they completed the tasks, with a researcher observing their interaction with the simulation. At the conclusion of the session, participants were asked to complete a post-test and a survey questionnaire regarding their perception of the experience.

<u>Instruments:</u> The pre- and post-test contained five identical questions based on the learning goals of the first four simulation sequences S1-S4, designed to measure the learning outcomes of the simulations in isolation. The pre-/post-test questions included multiple choice, select all that apply, and short answer responses, as shown in Table 2. The post experience survey questionnaire contained items that asked participants to rate their learning experience, including ease of use, engagement, and effectiveness of the simulation (Table 3), what they liked most and least about the experience, any difficulties they had with the simulations, and how the tool could be improved. They were also given six questions based on the NASA Task Load Index (TLX) to gauge perceived workload.

<u>Data Analysis and Results:</u> Analysis of the pre- and post-test scores showed large gains in participants' understanding of the basics of process control. The mean score for the pre-test was 32.5%, whereas the mean score for the same five questions on the post-test was 85%. All eight participants were able to answer Q4 correctly in both the pre-test and post-test, indicating they

were familiar with distribution curves. Only one student received any marks for questions Q1-Q3 in the pre-test, with most students gaining full or partial credit after the simulations.

ID	Pre-/Post-Test Question (N = 8)	Mean Pre-Test Scores (%)	Mean Post-Test Scores (%)
Q1	Which of the following are the most common defects that occur in plastic injection molded products? Select all that apply. (Flash, Plane Sheer, Cold Shut, Short Shot)	12.50	87.50
Q2	What is the purpose of a run chart in process control?	0.00	87.50
Q3	What is the purpose of a histogram in process control?	12.50	81.25
Q4	When measuring a manufacturing output of a process that is in control, what distribution curve is expected? (Poisson Binomial Distribution, Normal/Gaussian Distribution, Bimodal Distribution, Uniform Distribution.)	100.00	100.00
Q5	In manufacturing process control, what is the reason for sampling the output, and continuously calculating the mean (average) and standard deviation (spread) of the data in each sample?	37.50	68.75
	Total Mean Test Scores	**32.50**	**85.00**

Table 2. Pre-test and post-test questions administered in the simulation-only user study.

Overall, the participants reported the simulations were easy to use, engaging, and effective at introducing the basics of process control. The first three questions of the survey results are shown in Table 3. It will be important to confirm this result both with the second target audience of industry technicians, and with a larger cohort of undergraduate students.

Item (N = 8)	Strongly Disagree (1)					Strongly Agree (7)		Mean
	1	**2**	**3**	**4**	**5**	**6**	**7**	
I thought the system was easy to use.	0%	0%	0%	12.5%	37.5%	12.5%	37.5%	**5.75**
I found the simulation engaging.	0%	0%	0%	14.3%	42.9%	28.6%	14.3%	**5.43**
The simulation was effective in teaching the basics of process control.	0%	0%	0%	0%	25%	25%	50%	**6.25**

Table 3. Survey of user satisfaction from the simulation-only user study.

In addition, the overall task load index was calculated to be a value of 23.65, which is categorized as a medium task load and indicates the simulation was well-paced and did not have significant cognitive overload for the undergraduate students. Five of the eight students were not able to complete the final step of the S4 sequence (producing 200 gears) in the allotted time due to browser performance, which caused gears to be produced slowly.

Pre-/Post-Test Question (N = 8): Very Low (0) – Very High (100)	Mean Response
How mentally demanding was the task?	30.00
How physically demanding was the task?	5.63
How hurried or rushed was the pace of the task?	17.50
How successful were you in accomplishing what you were asked to do?	48.13
How hard did you have to work to accomplish your level of performance?	23.75
How insecure, discouraged, irritated, stressed, and annoyed were you?	16.88
Total Mean Response	**23.65**

Table 4. Survey results for NASA Task Load Index (TLX) from the simulation-only user study.

Feedback from the students was generally positive, with one student asserting "…[a] simulation is a helpful way to display this information in a way that the user can interact with. I appreciated that it used realistic situations (if a little simplified) and data. Graphs were effective." When asked what they did not like about the simulations, students highlighted a few elements in the user interface which were difficult to control, such as the sliding bar to control barrel temperature, and the fact that the web simulation ran slowly in-browser on a few of the students' laptops. One student remarked: "There was a lot of dead/waiting time as gears were being produced." Most of the students reported that they found the interactive graphs and curve fitting to be an intuitive and effective learning tool.

<u>Actions and Takeaways:</u> The development team redesigned elements of the UI and addressed in-browser performance issues on low performance computers in sequence S4. The team made modifications to the pacing of the simulation sequences, with a fast forward button and the option to skip the animations of the injection-molding gear production. The "think-aloud" sessions provided useful feedback to the research and development team and highlighted the need to give students greater autonomy earlier in the S2 simulation sequence.

4.2. Future Work: Pilot Testing the Full SPC Module and Summative Research

The research team will conduct assessments of the full statistical process control learning module (videos, exercises, simulations/game, and labs) during two phases: with small groups of students in pilot programs in early 2025, and the during the full deployment of a one-year technologist training certification program in the fall term of 2025. The assessment instruments will be refined and expanded to measure the efficacy of the full learning module. The final module will be deployed at six community colleges in the fall term as part of a one-year manufacturing certificate program. The research team will measure overall learning gains, engagement, and intrinsic motivation in a presence/absence study to identify differences between cohorts with and without the interactive simulations. The team is also interested in comparing learning outcomes between undergraduates and technicians enrolled in manufacturing workforce training programs.

5. Conclusion

Through interactive simulations, game-based learning, and blended learning modules we have created an engaging learning experience that leverages the many advantages of digital manufacturing environments to teach statistical process control. The primary target audience is incumbent manufacturing technicians and community college students, and we believe the simulation/game and the blended learning module is also appropriate for undergraduate audiences. While the development of web/mobile graphing tools using an iterative multidisciplinary design approach can be resource intensive, the simulation and learning modules can be used at scale in many manufacturing programs. The interactive graphs, GUI design, and data visualization techniques developed in this work could also be adapted to teach more advanced SPC topics such as multi-process manufacturing systems or run-to-run batch process control for the semiconductor industry.

Acknowledgement

This work is supported by the Industrial Base Analysis and Sustainment (IBAS) program. The authors thank Prof. David Hardt (MIT) for online lecture content creation and feedback during development. Special thanks to Pete Schupska (OSU) for injection molding subject matter expertise and Vimal Buck (OSU) for recruitment of student participants.

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