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A Human-Centric Engineering Education Model Inspired from Modern Manufacturing Processes

Dr. Y. Curtis Wang, California State University, Los Angeles

Y. Curtis Wang is with the Electrical and Computer Engineering department at California State University, Los Angeles.

Prof. Jim Kuo, California State University, Los Angeles

Jim Kuo is an Assistant Professor in the Department of Mechanical Engineering at California State University, Los Angeles.

Dr. He Shen, California State University, Los Angeles

He Shen is currently with Department of Mechanical Engineering at California State University, Los Angeles. His research interests include robotics and control, as well as engineering education.

Dr. David E. Raymond, California State University, Los Angeles

Dr. Raymond is an associate professor of mechanical engineering at Cal State LA. His teaching focus is on fundamental solid mechanics courses. His research interests are in the area of applied injury biomechanics and engineering pedagogy.

Mr. Mathias J. Brieu, California State University, Los Angeles

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Abstract

In the traditional factory-based engineering education model, schools are modeled as factories, where students are often superficially viewed as raw materials or unfinished parts which undergo a series of cold, machine-like value-adding processes before graduation. Critics of this model are often unsatisfied with the non-individualized dimensions of a rigid, collective mechanistic cultural production model. However, manufacturing processes and workflows in modern (2000s and beyond) production environments have become tailored for employee autonomy and product customization, offering an opportunity to re-examine the traditional factory-based engineering education model and develop new synergies for balancing efficiency and individualization.

In this paper, we examine and expand on this factory-based metaphor by proposing an updated human-centric engineering education model based on modern manufacturing processes to demonstrate that efficiency does not have to be antagonistic to individualization. Several tenets of manufacturing and production workflows that can be adapted to an educational environment are identified, such as the Toyota Production System (TPS) workflow. In particular, our example model focuses on the principles of respect for people, continuous improvement, and visual control. Utilizing these principles from modern industry can capture both the humanistic and consistency components required by engineering education for students to draw important insights.

Within this updated model, instead of viewing students as products, students are viewed as employees. In this view, students develop the engineering knowledge and skills they need for their career, akin to employees producing products to a specification. As with an assembled product, the quality of the value-added process at each stage of a manufacturing process directly impacts downstream components, especially if there is a direct reliance for a particular requirement. For example, calculus is required in nearly all engineering courses, and competency in calculus can be analogous to quality of an input stage early in the manufacturing process initiated by the employee.

Finally, we present a learner-centered course redesign of a statics course to show the applicability of modern manufacturing principles towards improving engineering education. This redesign demonstrates that a mastery-based course structure is consistent with our updated model and TPS principles. In this redesign, a continuous and iterative process was employed to ensure continuous improvement, and it follows a closed loop pattern of diagnosis, analysis, design, implementation, and evaluation (diagnosis).

I. Introduction

The factory model for education is based on Taylorism and principles of 'scientific management' [1]. This factory management system was developed in the late 19th century and emphasized on top-down management and power, and standardization and simplification of tasks in order to maximize efficiency [2], shown in Figure 1. Parts and materials enter an assembly line and undergo numerous processes applied by factory workers, prescribed by line supervisors. After passing the final quality check, the finished products are ready to be shipped. Although Taylorism has largely vanished from contemporary workplace, many have argued that education systems of today are still rooted in Taylorism, or ‘factory model’ for education [1], [3].

In the factory model, learners are treated as parts and materials, in which standard curricula, tests, and teaching pedagogies are applied to shape learners into finished products that are needed by the society [4], [5]. The analogy between the factory model and its counterpart in education is shown in Figure 2. In this view, instructors teach subjects in a sequential manner as prescribed by department-level and college-level administration such that by the end of the program, standardization of graduates can be achieved. Critics of this education model argue that this model emphasizes on conformity and standardization, centered on standard tasks, stifles innovation, and perpetuates inequity based on race and class [6]. Furthermore, most education systems cohort students by age, in which learning deficits are compounded over time [4].

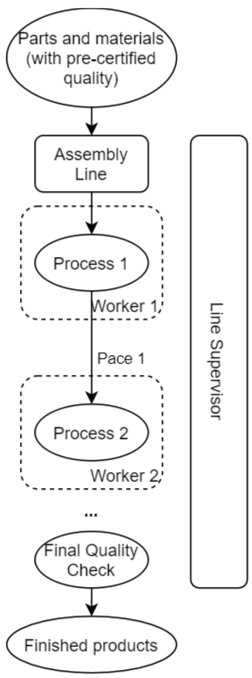

Figure 1: Taylorism applied to manufacturing

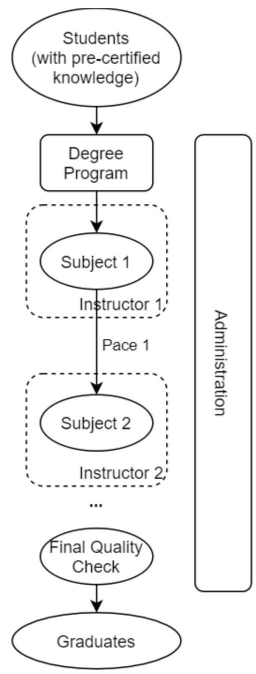

Figure 2: Taylorism applied to education

Table 1: Top-down, task-centric factory model

Factory	**Education**
Parts and materials (with quality certified by supplier)	Students (with prerequisites certified by prev. institution)
Finished product	Graduates
Line workers	Instructors
Line supervisors	Administration
Process	Subject
Assembly Line	Degree Program

However, today's modern manufacturing processes have evolved unrecognizably from their distant cousins in the 19th century. Modern successful manufacturing companies need to be innovative, sustainable, flexible, and data driven, and have moved away from being task-centric organizations to human-centric production systems [7]. Similar trends have been observed in education toward a transition to learner-centered model [5], [8]–[10], where learners are expected to be in the 'driver's seat' in their learning process. A number of studies have presented ideas on how to rethink and reshape current education [11]–[14]. In this paper, we present a new perspective of modern manufacturing process, and reveal the application of some human-centric principles in modern manufacturing process for a learner-centered education with improved efficiency and effectiveness.

The rest of this paper is organized as follows. In Section II, principles of a modern manufacturing process are reviewed, then a new education model is derived to show that modern manufacturing principles are consistent with learner-centered education. The implications of this new model, and its applicability in a course redesign are discussed in Section III. Finally, conclusions are drawn in Section IV.

II. New Perspectives to Modern Manufacturing Processes and Learner-Centered Education

Manufacturing trends have shifted since the 19th century to include a combination of intercultural exchange, advances in technology and operation research, and increasingly-specific customer needs. This has driven changes in manufacturing towards more flexible approaches, including mass customization [15]–[18]. Rather than maintaining a constant flow as prescribed during the 19th century, 21st century production lines have evolved to become more flexible and data driven. Operations research has driven the ability to perform mass customization, presenting a design of production lines as relatively autonomous operating units (distributed workload, rather than batch workload) in order to facilitate modularity [19]–[22]. This shift and re-envisioning of the manufacturing workplace, along with new considerations in sustainability (both environmentally and financially) has also been formalized into a manufacturing model that focuses on a worker-centric, or human-centric, system [7]. Figure 3 shows an example of this human-centric system, where the pace and production flow, once the specification is input, is controlled by workers. Within this section, we present an overview of many changes made in manufacturing and the potential and documented effects of these changes.

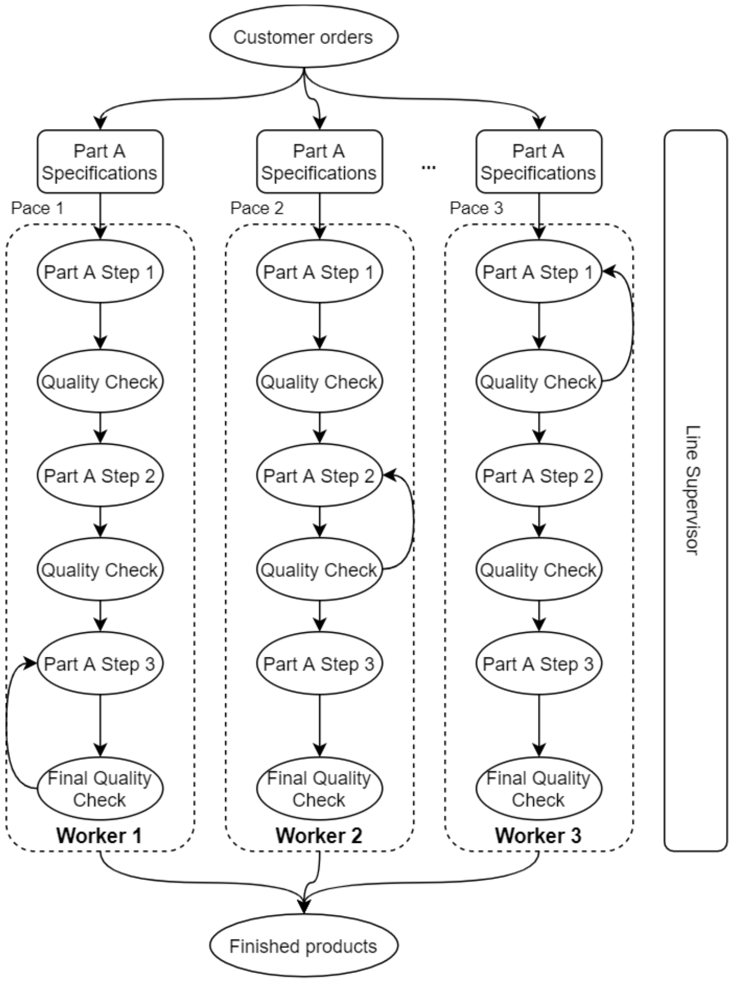

Figure 3: Example structure of a human-centric manufacturing model, where each line is flexible to the worker manufacturing the part due to integrated quality control loops, allowing for autonomous work pacing and specification customizations.

Toyota Motor Corporation is often one of the companies that many look towards when discussing modern manufacturing principles and human-centric business philosophies [15]–[17], [23]. While Toyota is often regarded as a conservative company, their manufacturing system, the Toyota Production System (TPS, often called Lean), has influenced much of the modern manufacturing industry. The key 14 principles of the Toyota Way show the human-centric evolution of manufacturing businesses from the days of scientific management [15]:

1. Base your management decisions on a long-term philosophy, even at the expense of short-term financial goals.
2. Create continuous process flow to bring problems to the surface.
3. Use “pull” systems to avoid overproduction.
4. Level out the workload (heijunka). Work like the tortoise, not the hare.
5. Build a culture of stopping to fix problems, to get quality right the first time.
6. Standardized tasks are the foundation for continuous improvement and employee empowerment.
7. Use visual control so no problems are hidden.
8. Use only reliable, thoroughly tested technology that serves your people and processes.

9. Grow leaders who thoroughly understand the work, live the philosophy, and teach it to others.
10. Develop exceptional people and teams who follow your company's philosophy.
11. Respect your extended network of partners and suppliers by challenging them and helping them improve.
12. Go and see for yourself to thoroughly understand the situation (genchi genbutsu).
13. Make decisions slowly by consensus, thoroughly considering all options; implement decisions rapidly.
14. Become a learning organization through relentless reflection (hansei) and continuous improvement (kaizen).

One may notice that the principles do not directly specify a manufacturing process, but rather, they specify guidelines for company culture. There is a focus on three concepts throughout these principles, particularly: **respect for people, continuous improvement, and visual control** [15]. The first principle, in particular, seems antithetical to the idea of mass manufacturing – rather than focus on achieving immediate profitability, the Toyota system focuses on achieving eventual profitability through long-term investments. The Toyota system instead focuses on building consensus, direct visual understanding, and ensuring accuracy and reliability to minimize waste, rather than pushing for raw manufacturing throughput.

This foundational system has provided a base for many production processes and improvements, even within software development, such as Lean software practices (e.g., test-driven development) [24]. Non-automobile companies, such as John Deere, Siemens, Electrolux, and Lego have implemented their own refinements of the Toyota Production System; a 2013 review [25] of the XPS (X-company production systems, each company's refined process) shows that the top 7 principles are (in order of % implemented): standardized work, continuous improvement, total quality, pull system, value stream, employee involvement, visualization, customer focus, and stability/robustness. Depending on the industry, different aspects of the TPS principles are used. Some companies decide not to place emphasis on the people-oriented aspects, but these are not the majority of the implementations. Overall, much of modern manufacturing has shifted from cold machinations towards more flexible, people- and demand-based approaches.

We propose an updated education model based on the modern human-centric manufacturing such that modern manufacturing principles can be applied in education reforms. In this model, we view students as employees and instructors as supervisors, shown in Table 2. The learning materials are treated as parts and materials in which students will work on in which the finished product will be the knowledge and skillsets developed during the learning process. In the remainder of this section, we show that the TPS principles are consistent with that of learner-centered education.

Table 2: Modern human-centric manufacturing model

Modern Manufacturing	Education
Employees	Students
Supervisors	Instructors
Parts and materials (consumables)	Learning materials
Finished product	Learning outcomes (knowledge and skillsets)
Process	Learning and/or Instruction
Problems	Problems
Quality	Quality

There are five major characteristics in learner-centered education [26], [27]. First, Weimer [26] believes that teachers are doing too much learning for learners, and instead should involve learners in doing less refined tasks (e.g. identify problems and tasks) before moving on to develop more refined abilities. This is consistent with TPS principles 2, 7, 12, and 14 of developing a process in which problems can be clearly identified and understood by the learners through continuous reflection. Second, Weimer argues that educators cannot assume learners will pick up skills on their own and that skills should be developed explicitly along with the content for learners to think critically, apply information, and integrate knowledge. This is consistent with TPS principles 2, 6, and 7 which emphasize on identification and communication of problems while providing structured learning for learners. Third, learners need to reflect on the how, what, and why in their learning and take responsibility of their learning decisions. This is similar to TPS principles 1, 4, 12, 13 and 14, where learners need to take a long-term consistent and sustainable approach in their learning where choices are consciously made through continuous reflection and deliberation with others. Fourth, teachers should hand over some control of learning to students, and this is consistent to TPS 3, 4, 5, 6, and 13. These principles describe empowering learners to make some decisions on the content, pace, and method of their learning through consensus. Lastly, learner-centered education encourages collaboration and promotes a community of shared learning commitments, and is consistent with TPS principles 1, 9, 10, and 14. These principles emphasize on long-term learner success by fostering a supporting community with shared learning philosophy.

III. Implications on engineering education

The focus on **respect for people, continuous improvement, and visual control** within modern human-centric manufacturing principles can be incorporated into engineering education. The main idea, from the educational viewpoint, is not to copy/paste industrial processes as is, but rather to draw inspirations from industry analysis procedures as a way to improve education. The proposed model enables beneficial application of well-established TPS principles to re-think education.

Consider a course (e.g. statics course) with specific learning outcomes in which students need to master the specific learning outcomes (knowledge and skillset) by the end of the course. In this model, students are the individual workers responsible for the work, which is analogous to learning, shown in Table 2. In modern manufacturing, workers and supervisors work together to design a process by considering respect for people, continuous improvement, and visual control. Figure 4 shows how this customizable and structured learner-centered approach could be applied. It illustrates three possible pathways in which learners can take to reach the learning outcome, where learners learn the same content at different paces with autonomy, while receiving feedback at a different frequency depending on the needs of learners.

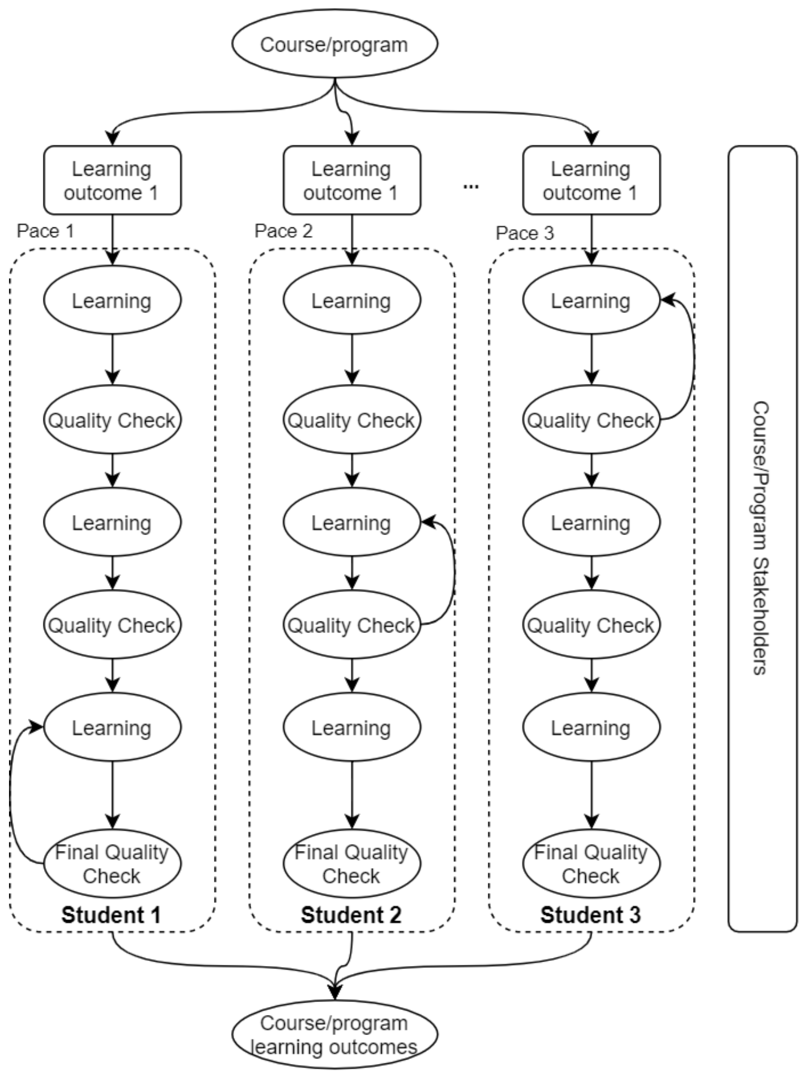

Figure 4: An example customizable base instructional structure in a course incorporating TPS principles using the proposed model, where students work through learning and building their skills and knowledge at individual paces. This result is consistent with mastery-based learning.

Here we discuss a redesign of an undergraduate gateway course, ME 2010: Statics. The redesign was done without prior knowledge of TPS principles and before development of the proposed model. However, after re-design we recognized that the process and new mastery-based course structure are consistent with the proposed model and TPS principles. In this redesign, a continuous and iterative process was employed to ensure continuous improvement, and it follows a closed loop pattern of diagnosis, analysis, design, implementation, and evaluation (diagnosis). The detailed steps are explained as follows.

Step 1: Diagnosis

As of the fall 2019 semester, the department had been observing a trend, for more than five years, that the non-completion rate (e.g., failure, withdrawal, and incomplete) of statics was the highest of any other mechanical engineering course in the undergraduate curriculum. Thus, this represented the identification of the first quantitative criterion used to assess the "health" of the course design: the non-completion rate. A discussion amongst department faculty members was subsequently initiated for redesigning the course with an aim to improve the non-completion rate. This discussion led us to identify a second concern, which was that the statics knowledge and skills of students who *passed* the course could not meet faculty expectations in downstream courses within the program. We, therefore, identified a second evaluation criterion regarding the quality of the course: the mastery level of specific knowledge and skills of students passing the class. The quantitative parameter identified to be the most closely related to this criterion was the rate of success of students in the subsequent courses following statics (e.g., strength of materials, dynamics).

Step 2: Analysis

A root-cause analysis was subsequently undertaken once the two quantitative criteria were identified. This analysis led to the following conclusions:

1. The high non-completion rate is likely linked to:
    a. The pace of the course, which may not correspond to the preparedness of the students entering the course.
    b. Inconsistencies in the grading practices of instructors teaching the course.
    c. Instructor-centric pedagogies.
2. The inadequacies of students' statics knowledge and skills for those passing the course is likely linked to:
    a. A misalignment of expected learning outcomes for the statics course.
    b. Inconsistencies in learning outcomes, course content and topical emphasis by various statics instructors.
    c. Inconsistences in grading schemes and learning outcome validation across various statics instructors.

Step 3: Designing a learner-centered course

The main philosophy used in the course redesign was to empower students to take ownership of their learning and become the main contributor to their development. The overarching goal was to provide a student-centered learning environment which was based upon an improved alignment of learning outcomes and clear, unambiguous grading criteria which is independent of the instructor. To achieve this goal, the first aim was to develop clear, hierarchical, learning outcomes based upon input and buy-in from all mechanical engineering faculty (TPS 2, 4, 5, 11-13). This was done to ensure that learning outcomes were leading to the development of knowledge and skills that met the expectation of faculty teaching subsequent courses in the curriculum as well as to achieve consistency across instructors teaching the course. The second aim was to propose a learner-centered strategy of instruction which fosters improved student motivation, embraces the importance of learning from failure without penalty, and allows for individualized pacing to meet each students' unique needs and backgrounds (TPS 4, 5, 6, 10, 12).

Step 4: Implementation and evaluation of the developed course.

The pedagogical approach developed for this course is rooted in mastery-based learning philosophy [28]. The course was broken down into nine hierarchical learning outcomes. Each learning outcome was associated with a specific teaching module. Each teaching module was comprised of assigned reading, lectures, homework problems, (TPS 6) and low-stakes self-evaluation quizzes (TPS 7). A flipped classroom was utilized for face-to-face meetings prior to the pandemic which allowed for student-centered activities (TPS 9, 12) rather than classical lectures. Validation of each learning outcome was demonstrated by the successful completion of exam problems tied to the specific learning outcome. Exams were evaluated using a mastery-based rubric and normed grading (TPS 5, 6, 7, 8). To receive credit, students must show mastery of the learning outcome. No partial credit or points are assigned under this scheme, which was found to remove students' emphasis on attaining "credits" and focused them more on actually achieving the defined learning outcome (TPS 5, 9, 11). If the learning outcome is met, the student can move on to the next module and learning outcome. If the student does not achieve mastery on an evaluation, there is no penalty and the student may continue to work on this module, correct his/her learning process by receiving instructor feedback, and retake the evaluation at a later date (TPS 2, 3, 5, 7, 14). The key is that students are not penalized for failing to keep pace with other students but are still expected to achieve mastery of specific learning outcomes before they may progress on to higher level course content and pass the class. The final course grade is determined by how many of the learning outcomes were successfully mastered on the exams. In order to receive a passing grade (C grade), students need to demonstrate mastery of three learning outcomes designated by the faculty as the most fundamental statics concepts. These were defined as learning outcomes C1, C2 and C3, shown in Table 3. Subsequent learning outcomes (B1, B2, B3, and A1, A2, A3, shown in Table 3) build upon C-level concepts and serve to improve a student's grade.

Table 3: Learning objectives in ME 2010: Statics course. Students need to master C-level concepts before continuing onto subsequent levels.

	Learning Objectives
C-level	**C1:** Solve 2D equilibrium problems involving dry friction.
	C2: Solve 2D equilibrium problems involving frames and machines under point loads and basic (uniform, triangular) distributed loadings.
	C3: Solve for internal shear / normal forces and internal bending moment of cantilever and simply-supported beams exposed to external point loads.
B-level	**B1:** Solve 2D equilibrium problems involving basic machine elements (wedges, screws, rolling resistance).
	B2: Solve for centroids of objects using the "composite" method.
	B3: Solve for internal forces and moments in beams subjected to basic distributed loadings (uniform, triangular) and draw the corresponding shear and moment diagrams.
A-level	**A1:** Solve 3D equilibrium problems involving concurrent force and rigid body systems.
	A2: Solve for centroids of volumes using "composite" method.
	A3: Locate minimums and maximums on shear/moment diagrams.

Using this overall structure and philosophy, students can self-pace their learning of the course material and are provided multiple attempts throughout the entire semester to demonstrate mastery of the most fundamental course concepts. This maximizes the time allocated for personal development and combined with instructor feedback on evaluations, increases student confidence in their progress toward reaching mastery (TPS 9, 10, 11, 14). The redesigned learning outcomes have faculty buy-in and have been aligned with the expectations set forth by faculty teaching subsequent courses. Finally, instructor-dependent grading methods and expectations have been removed through the implementation of normed mastery-based grading practice.

Step 5: Evaluation and corrective actions

As mentioned earlier, two criteria were developed from an analysis of the course: Non-completion rate and the performance of students in the subsequent courses. Since the implementation of the mastery-based learning approach, the non-completion rate has been reduced by 57% and now has one of the lowest non-completion rates of any course in the curriculum. The grade distribution of the course from Spring 2019, Fall 2019, and Spring 2020 is shown in Figure 5. The performance of students in following upper-level courses is currently under investigation.

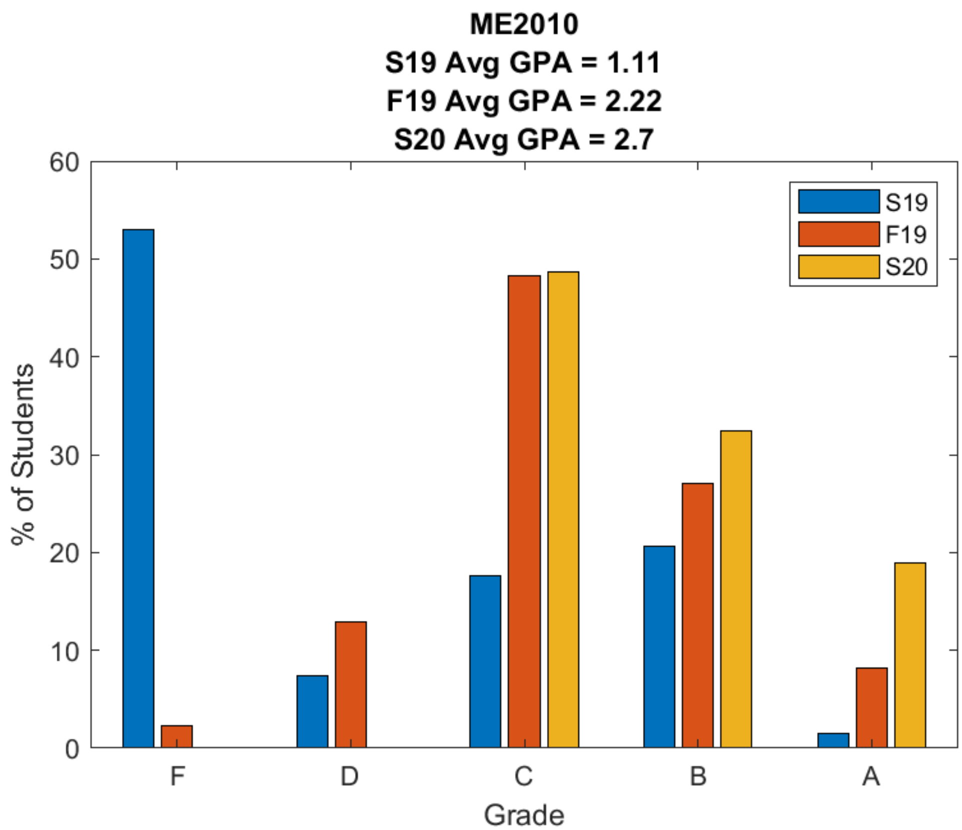

Figure 5: Grade distribution of ME 2010: Statics. Mastery-based learning was implemented in Fall 2019 and Spring 2020.

Figure 6 illustrates the structure of the mastery-learning approach. A flexible learning structure has been developed, in which learners take charge of their learning, and are able to make decisions on the pace and content of their learning while keeping the learning content standardized. Continuous feedback is provided to learners at various stages with an emphasis on quality, congruent with the course structure described in Figure 4. Furthermore, while the redesign of this course was not driven by TPS principles, we noted many similarities between our approach and TPS principles. For example, in addition to designing a learner-centered course, we recognized the importance of exhaustive documentation of our processes to implement strategies of follow-up and make continuous improvement. This continuous improvement allowed us during the first semester to lower the failure rate, and during the subsequent semesters to reduce not only the rate of students dismissing or withdrawn but also improve the overall level of GPA by 0.5.

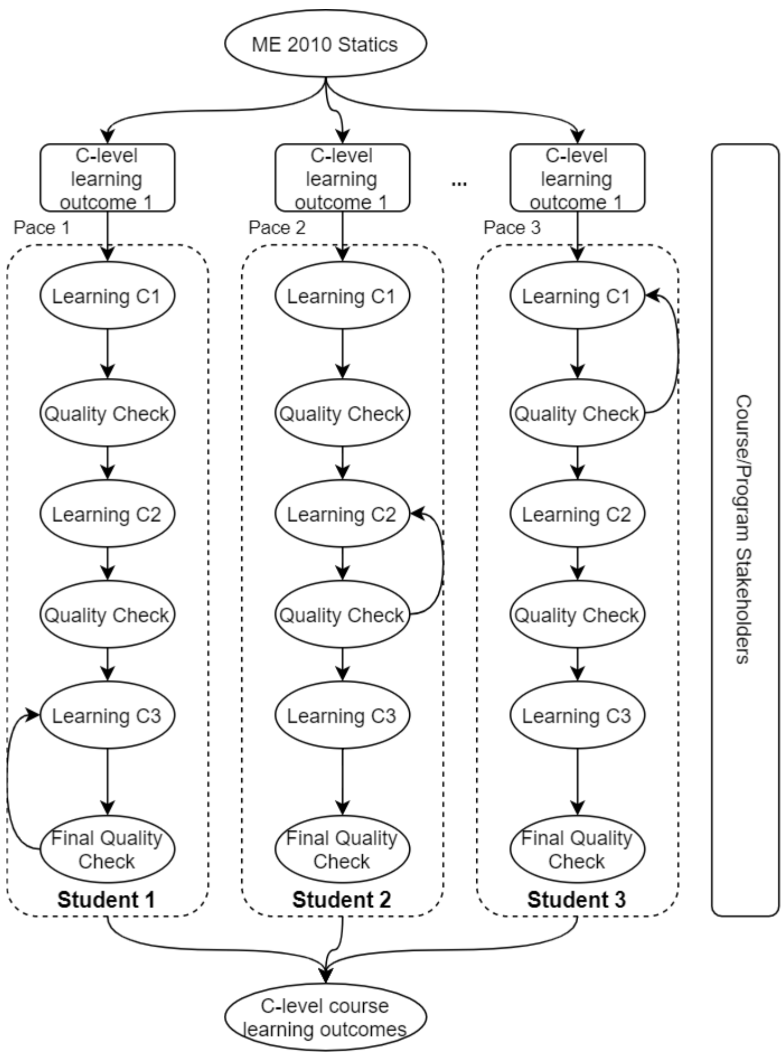

Figure 6: Updated course workflow for C-level learning outcome 1 in ME 2010. Once students have successfully validated their C-level learning outcomes (e.g. C1, C2, C3), they continue through the B-level workflow, which is similar to the structure described in Figure 4. Students work through building their knowledge and skillset at their own pace to ensure that they achieve the C-level learning outcomes within the first enrollment of the course.

IV. Conclusion

Modern factories have witnessed a significant shift from a task-centric model to human-centric model, where long-term employee development is valued. Different from the traditional view of factory model education where students are seen identical products of a manufacturing line, this paper provides a new perspective of a modern manufacturing education model. Herein, students are regarded as workers while products are learning outcomes (knowledge and skillsets). Students are provided with flexibility to master desired learning outcomes on their own paces following their preferred way of learning. The core values of this education model are a subset of the TPS principles, primarily the principles of respect for people, continuous improvement, and visual control. A comparison of the 14 principles of TPS with the five major characteristics of learner-centered education reveals their strong correlations. Although the proposed model was not directly applied, consistency between the proposed model and the mastery learning approach was demonstrated. The demonstrated example used to illustrate the application of the proposed educational model and TPS principles was the mastery-based redesign process of a gateway course, ME 2010 Statics, in mechanical engineering. Significant improvement was observed from this preliminary study, which inspires the team to carry out a long-term and in-depth study of the implementation of the proposed education model.

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