Productive Failure Pedagogy in Engineering Mechanics

Persaud, Stefan ; Flipsen, Bas

DOI
10.35199/EPDE.2023.58

Publication date
2023

Document Version
Final published version

Published in
DS 123

Citation (APA)
Persaud, S., & Flipsen, B. (2023). Productive Failure Pedagogy in Engineering Mechanics. In I. Ordóñez, P. Sustersic, L. Buck, H. Grierson, & E. Bohemia (Eds.), *DS 123: Proceedings of the International Conference on Engineering and Product Design Education (E&PDE 2023)* Article 1219 (E&PDE). The Design Society, Institution of Engineering Designers. https://doi.org/10.35199/EPDE.2023.58

25TH INTERNATIONAL CONFERENCE ON ENGINEERING AND PRODUCT DESIGN EDUCATION
7-8 SEPTEMBER 2023, ELISAVA UNIVERSITY SCHOOL OF DESIGN AND ENGINEERING, BARCELONA, SPAIN

PRODUCTIVE FAILURE PEDAGOGY IN ENGINEERING MECHANICS

Stefan PERSAUD and Bas FLIPSEN
Industrial Design Engineering, Delft University of Technology, Delft, The Netherlands

ABSTRACT
In September 2021, the faculty of Industrial Design Engineering (IDE) introduced a revamped bachelor's programme that emphasizes design for higher complexity, teacher as a coach, and autonomous learning. The programme includes Understanding Product Engineering (UPE), which teaches first-year design students about product embodiment, manufacturing, and mechanics of materials. However, the traditional approach of teaching engineering using direct instructions and problem-based learning was ineffective, as students failed to apply the engineering knowledge in their capstone design projects.
To address this issue and promote autonomous learning, the Productive Failure (PF) pedagogical framework was introduced as the main pedagogical framework in UPE. However, the general approach of the PF pedagogy as described by Kapur, lacked a translation into an effective design of the workshops. To address this, this paper proposes a hands-on model based on constructive alignment, where learning objectives, activities, and assessment are designed side-by-side. This paper presents our didactical model, which was developed in an agile way during the second run of UPE. The hands-on model proposed aids in applying the PF pedagogy in engineering courses and consists of a method to develop workshop assignments and a didactical approach to guide and coach students through the workshop process.

Keywords: Autonomous learning, productive failure, direct instruction, product engineering, engineering mechanics

1 INTRODUCTION
In September 2021, the faculty of Industrial Design Engineering implemented a new bachelor's programme, which includes over 335 first-year students. The curriculum has been updated to reflect changes in the industrial design profession, with courses in technology, organizations, people, data, digital interfaces, and understanding values [1]. The new approach involves semester-long design courses where students apply theory and skills learned in parallel theoretical courses, promoting an autonomous learning attitude. This approach requires a different teaching style, with teachers acting as facilitators rather than instructors.
The Faculty of Industrial Design Engineering previously taught mechanics through direct instruction [2] but found that students were not applying the knowledge in their design projects. To address this, we introduced an autonomous learning approach in the course Understanding Product Engineering (UPE), using the theory of Productive Failure (PF) to promote experiential learning [3-5]. Students solve unguided problems, generating suboptimal or incorrect solutions that are used to provide insights into their lack of knowledge and guide them towards relevant solutions. However, during the first few weeks, students and teachers found it difficult to transition from the ingrained instruction-based learning to a more autonomous learning. We struggled to move from phase one of PF, where students generate and explore multiple representations and solution methods, to phase two, where discoveries are linked to theory [3]. To address this, we changed the workshop structure, stimulating collaboration between students and switching roles between facilitator and instructor. We also created a safe space for the teaching staff, increasing mutual student-teacher respect and trust through dialogue and positive coaching techniques.
Based on our reflections and students' feedback we found out that some workshops worked better than others, but we also concluded that the general approach of the PF pedagogy was lacking a translation into an effective design of the workshops. In hindsight, we learned to design workshops by dissecting

course learning objectives into related concepts, identifying knowledge gaps, and designing exercises around them. During the process we also learned that a safe space to experiment and making mistakes, together with a clear timeframe, is key to successful learning [3].
To help us out in applying PF in a more structured way, we have designed a new didactical model to develop and execute the workshops in the future which considers our previous iterative learnings using design-based research. This didactical model is our next iteration for applying PF pedagogy in our mechanical engineering course. This paper will introduce this didactical model, the Productive Failure Design Cycle, starting with a stepwise model to develop a workshop in six steps, followed by a model to execute the workshop in four phases, following both the exploration and consolidating phases of PF according to Kapur [4,5].

2 APPROACHES

Despite the potential of the PF pedagogy, the general approach described by Kapur [4,5] lacked a translation into an effective design of the workshops. To make it more applicable we used design-based research where we have gone through weekly iterations improving the model with every iteration [6]. The course spans over a 10-week quarter consisting of 8 lectures and workshops to meet the learning objectives of the course. Each week, one or two learning objectives are addressed, followed by a design of the workshop based on the previous year's materials. We used the basic design cycle [7] as a framework to improve our model over the weekly iterations. During the week we noted down the didactical approach from a draft version at the start of the course to a final model nearing the end of the course. Using short design sprints, we weekly improved the didactical approach. We dissected the workshop in more detail every week, reinforcing improvements and filtering out weaknesses which enriched the model in every step to a more solid final model in week 8.

3 RESULTS

To be able to apply the basics of Productive Failure, we have developed a practically applicable didactical model for our course Understanding Product Engineering (UPE) consisting of two parts, designing a PF structured workshop assignment, and designing an implementation model for the workshop.

3.1 Workshop assignment design

The first phase Kapur describes is "Generation and Exploration of RSMs (Representation and Solution Methods)" which has the purpose of developing the right assignment [8,9]. The goal is to find "the sweet spot" of complex problems. Problems that are challenging yet not frustrating, that address prior knowledge and have an affective draw to the students. To develop a workshop and incorporate Productive failure in a constructive aligned [10] educational way, we propose an iterative development cycle starting with a clear Learning Objective (LO), consisting of a core concept to be learned, and a related exam question. The proposed Productive Failure Design Cycle (PFDC) consists out of 6 steps (Figure 1):
Step 1 - Core Concept: The main goal of this first step is to identify the new knowledge or new skill the students need to learn. Derive the "Core Concept" from the defined LO you want to address, and describe the introduced knowledge, principle, or skill that has not been addressed in earlier education, and students do not yet know. If your course is not organized according to the constructive alignment principle [12,13] and Bloom's or SOLO taxonomy [14,15], you can still use defined learning goals or LO's of your course. Every week one or two LO's are addressed.
Step 2 - Exam Question: UPE and most other engineering courses are assessed with a written exam. Translate the LO into an exam question or use a previously used exam question. An exam question where students must calculate an outcome using formulas, to support design engineering decisions, is helpful.
Step 3 - Real Application: Think of a real-world engineering application of the knowledge or skill. In what situation would an engineer apply it. This helps both teacher and student to have a realistic context. We brought the real products and identified real designer's situations, like ordering pizza or beers at the student café, assembly of a bicycle bell, breaking or bending of a carabiner, Bill of Materials of a ballpoint pen, and so forth.

Step 4 - Problem: Define the problem the student must solve. To iteratively explore and deepen the problem and get to the root problem, we use the technique of asking WHY three to five times. It helps to get to the core of the problem.
Step 5 - Solution: Now take the problem and think of wrong solutions they can come up with, or which you came across when you were taught this concept. Think of the mistakes students will make because they do not know yet how to tackle it or make false assumptions due to the lack of knowledge. Make a list of what could possibly go wrong when people miss important knowledge or skills.
Step 6 - Redefine: Take the redefined problem and redesign the problem as a question: an assignment as a narrative with dialogue. It is important to check if the assignment can only be solved when students have access to the knowledge of the core concept, but where students can still try out things and are under the illusion, they can solve the problem using prior knowledge. Check if the assignment still addresses the core concept and has an affective draw of the problem scenario [16]. If not, redo the previous steps again.

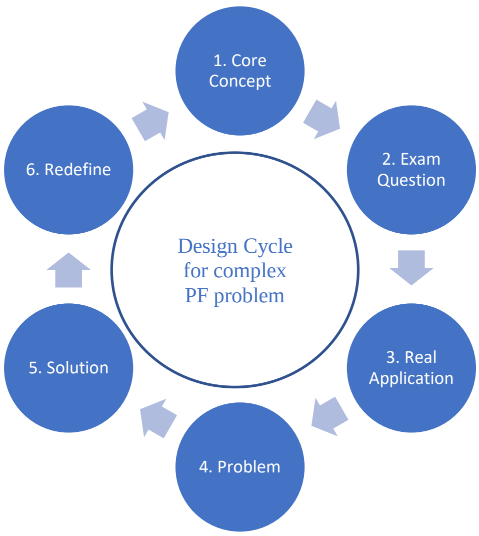

Figure 1. The proposed Productive Failure Design Cycle to come to PF based workshop assignment

3.2 Workshop implementation design

The workshop uses a time-guided set of workshop slides that introduce students to the challenging problem of the week, followed by a recorded instruction video and a problem they can solve using their new knowledge. Figure 2 shows some excerpts of the workshop slides.

Figure 2. Excerpts of a workshop: starting the workshop with a challenging problem students cannot solve with prior knowledge (top left), followed by a video-instruction explaining the concept (top right), after which students can work on a similar problem they can solve (bottom left) with its solution (bottom right)

To create an engaging and effective workshop, we took a meticulous approach to its design. Our iterative process led us to several key realizations that helped us “design the social surround for creating a safe space to explore” [16]. We discovered that using familiar vocabulary, such as the designer's language, created a comfortable and inclusive environment for both coach and student.
Drawing on this insight, we implemented the "basic design cycle" [6] as our process steps for the workshop, where, for instance, we rephrased “generation and exploration phase” to "ideation phase" that builds on the students' existing brainstorming skills. As design students they are used to developing multiple representations and solution methods (RSMs) and come to design solutions. In addition, our teachers also understood their role of managing the classroom in problem solving, instead of giving instructions on the objectives to learn.
Finally, we renamed the "Consolidation phase" as "Selecting and Trying" to reflect the design process more accurately. This change was embraced by both teachers and students, who found it easier to connect with the design perspective and bring their ideas to fruition. By thoughtfully redesigning the workshop, we were able to create a more engaging and empowering experience for all involved.
With 335 students in the course, we have divided the students into 14 studios, consisting of approximately 25 students coached by one teacher or teaching assistant. To facilitate a collaborative and engaging learning experience, each studio is equipped with a large screen that displays the workshop's materials. This technology allows students to easily follow along with the lesson and stay engaged throughout. Students are seated at tables with five to six peers creating an atmosphere of teamwork (Figure 3). The tables are outfitted with materials to participate fully in the workshop, including computers, whiteboards, and a wide range of materials like paper, markers, callipers, weighing scales, screwdrivers, and more.

Figure 3. Collaborative learning solving engineering problems using the whiteboard as a central tool

The workshop is divided in four phases as pictured in Figure 4 and explained underneath:
Phase 1 - Prepare: During the preparation students are introduced to a formative assessment in the form of a group quiz. The questions asked in the quiz give a view on possible exam questions or parts of it. The questions reflect retained knowledge from secondary school and knowledge from previous week(s). The quiz is time-bound, and answers are given after the quiz. The quiz activates foreknowledge and gives the students a sense of confidence. It also marks the start of the workshop and engages them in the day’s workshop.
Phase 2 – Ideation: During the ideation phase students are introduced to the problem, and brainstorm about differing solution strategies. After 10 minutes three possible strategies are explored to come to a solution to the problem introduced. The solutions are explored in depth, preferably in duos or as a group. Exception can be made to do it individually. The students make use of the whiteboard to make them explain their strategy to each other and engage other students in the collaborative thought process. At the end of this phase student groups present each other’s work to the rest of the students within the studio and discuss their findings, hurdles, and success or failure.

Phase 3 - Prototype: During the prototyping phase a video lecture is shown where students get the direct instruction of the knowledge needed to come to a correct solution for the problem presented. We make use of pre-recorded videos to have an equal explanation and instruction of the specific week's knowledge needed. We leave some autonomy to the studio's coach to enrich the explanations with personal experience and examples. After the instruction the student groups are exposed to a sort-alike problem in a new context and solve it individually to make the knowledge their own and confront the individual student to their own knowledge gaps.
Phase 4 – Evaluation: To close the workshop the students are presented with the correct worked-out answer to the second problem. In the studio the answer is discussed, and key-finding are drawn as a group. Students are asked to jot down their main important findings on their own personal note (cheat sheet), which they can bring to the final exam.
To have students exercise at home, we have developed several online questions using Möbius STEM software [17].

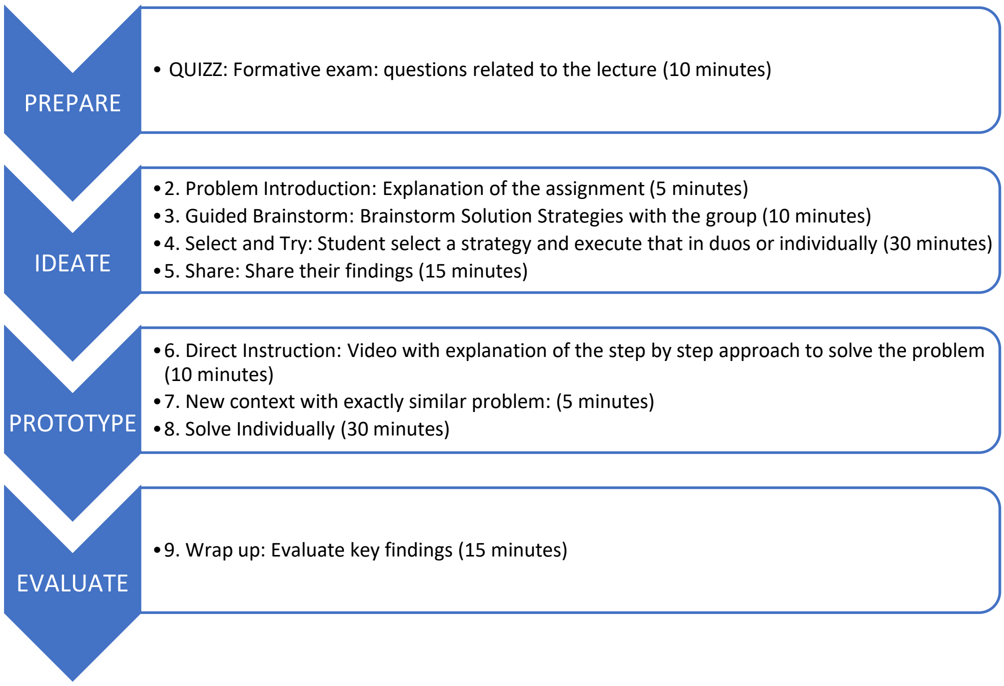

Figure 4. Workshop design: flow over one afternoon starting at 13:45 and ending at 17:30

4 DISCUSSION AND CONCLUSION

In 2021, we began implementing Productive Failure as our didactic framework for creating instructional materials and workshops. We quickly realized the need for a structured approach to guide us through the development process. During the most recent iteration of the course, our focus was on creating the Productive Failure Design Cycle. The objective was to design engaging and effective workshops and instructions not only for this particular course but also for future courses.
To achieve this, we adopted a weekly iterative design cycle consisting of six steps: core concept, exam question, real application, problem, solution, and redefine. Additionally, we established a four-phase didactic approach for workshop execution consisting of the following phases: prepare, ideate, prototype, and evaluate.
Collaborative brainstorming sessions involving the content expert of the week and some studio coaches proved to be the most effective method for developing workshops using the defined six steps. However, progressing from step 1 (core concept) to step 4 (a realistic assignment with productive failure) presented some challenges. This process requires a facilitator who guides the team and asks the right questions to refine and create a suitable assignment using the learning objectives as a starting point. Once the assignment was defined and aligned with the learning objectives for the week, describing the workshop became a straightforward task.
Based on our initial implementation in 2021, we recognized the importance of time management for the effectiveness of the workshops. To address this, we incorporated timers for each activity. Additionally,

since the instructions varied across different studios, we introduced weekly video instructions during phase 2 of the workshop to reduce reliance on individual coaches.

The time-paced approach and instructional videos helped the coach team stay on track with the content and made the workshops less dependent on specific studio arrangements. Consequently, there were fewer discussions with students regarding studio allocation. In this new context, the role of the studio coach shifted towards facilitation rather than traditional teaching or expertise. While some coaches initially perceived this change as a demotion, we realized that the coach's alignment with the PF pedagogy mattered more than their specific expertise. In fact, less-knowledgeable coaches, such as teaching assistants, could effectively guide the students.

Although we observed a slight improvement in the pass rates, it is essential to conduct further quantitative research to determine whether this can be attributed to the pedagogical framework. Additionally, qualitative research is necessary to explore the experiences of both students and teachers. We must also investigate knowledge retention in our UPE course, considering the positive effects of PF demonstrated in Kapur's research.

To evaluate the practicality of this method in different contexts, we successfully facilitated the PFDC in one new developed master course ID5422 Repair!. The next step is to document the design cycle in such a way that others can apply it in their own settings without our direct facilitation. As of now, the limited available data prevents us from drawing definitive conclusions regarding the effectiveness of the framework.

ACKNOWLEDGEMENT

This research was funded by the Education Fellowship grant (2022) at the Technical University Delft.

REFERENCES

[1] IDE (2022). Discover the IDE Bachelor. Website visited March 1, 2022: https://www.tudelft.nl/en/ide/education/bsc-industrial-design-engineering/programme

[2] Kirschner P. A., Sweller J. and Clark R. E. (2006). Why Minimal Guidance During Instruction Does Not Work: An Analysis of the Failure of Constructivist, Discovery, Problem-Based, Experiential, and Inquiry-Based Teaching. *Educational Psychologist*, 41:2, 75–86.

[3] Persaud S., Flipsen B. and Thomassen E. (2022). Productive Failure in Action, E&PDE 2022, 8-9 sept., London South Bank University, London.

[4] Kapur M. (2008). Productive failure. *Cognition and Instruction, 26*, 379–424.

[5] Kapur M. and Bielaczyc K. (2012). Designing for Productive Failure. *Journal of the Learning Sciences*, 21:1, 45–83.

[6] Schaber J. and Sutherland J. (2020). The Scrum Guide. Scrum.org.

[7] Van Boeijen A., Daalhuyzen J. and Zijlstra J. (2021). Delft Design Guide. BIS publishers, Amsterdam.

[8] Kapur M. (2014). Productive failure in learning math. *Cognitive Science*, 38(5), 1008–1022.

[9] Sinha T. and Kapur M. (2021). When problem solving followed by instruction works: Evidence for productive failure. *Review of Educational Research*, *91*(5), 761-798.

[10] Chowrira S. G., Smith K. M., Dubois P. J. *et al.* DIY productive failure: boosting performance in a large undergraduate biology course. *npj Sci. Learn.* **4**, 1 (2019).

[11] Kapur M. and Lee J. (2009). Designing for productive failure in mathematical problem solving. In Proceedings of the Annual Meeting of the Cognitive Science Society (Vol. 31, No. 31).

[12] Biggs J. (1996). Enhancing teaching through constructive alignment. High Educ 32, 347–364.

[13] Biggs J. (2014). Constructive alignment in university teaching. *HERDSA Review of Higher Education, 1*, 5-22

[14] Bloom B. S. (1956). Taxonomy of Educational Objectives, Handbook: The Cognitive Domain. David McKay, New York.

[15] Biggs J. and Collis K. (1982). Evaluating the quality of learning: The SOLO taxonomy. New York: Academic Press.

[16] Kapur M. and Bielaczyc K. (2012). Designing for productive failure. *Journal of the Learning Sciences*, *21*(1), 45–83.

[17] Möbius (2023). [STEM Computer software]. https://www.digitaled.com/