EXPERIENTIAL MACHINES TO ENHANCE LEARNING THROUGH PRODUCTIVE FAILURE

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ABSTRACT
The traditional approach of teaching engineering at the faculty of Industrial Design Engineering using direct instructions and problem-based learning was ineffective, as students failed to apply the engineering knowledge in their capstone design projects. Therefore, in the first-year engineering course Understanding Product Engineering (UPE), the Productive Failure (PF) method is used to teach mechanics of materials. Amongst other subjects, UPE includes modules on manufacturing techniques for plastics and metals, typically taught by theory alone. To address the challenge of practicing this knowledge and enhance their learning even more, a simple, safe, and cost-effective machine was introduced simulating thermoforming, injection moulding, and metal bending. This machine encourages experiential learning, which positively impacts knowledge retention and decision-making regarding material-manufacturing techniques.
To validate the student's enhancement in learning, an A/B test is executed which compares the PF approach using the experiential machine with traditional direct instruction (DI). Group A (nine students) used the machine and struggled before receiving instructional materials, while Group B (nine students) received direct instruction first. The students were interviewed on their experiences after the workshop and tested online on the content.
Results showed significant differences in student perceptions and experiences. Group A, using the experiential machines, felt more confident, enthusiastic, intrigued, and engaged compared to Group B. However, test scores of the exam a week later showed little differences between the two approaches.

Keywords: Experiential, productive failure, learning

1 INTRODUCTION
In September 2021, the faculty of Industrial Design Engineering at the Delft University of Technology implemented a new bachelor's programme, which includes over 335 first-year students. With the introduction of this renewed bachelor all courses underwent a revision to promote, amongst other, an autonomous learning attitude [1]. The conventional approach of teaching engineering relied on direct instructions and problem-based learning and proved to be inadequate, as students struggled to apply their engineering knowledge in capstone design projects [2]. To align with the new bachelor's approach in autonomous learning and to increase the application of engineering in capstone design projects, "productive failure" [3,4] was introduced as a new didactical approach within our first-year course, Understanding Product Engineering (UPE, IOB1-2) [5]. Productive failure flips the traditional learning process and starts with an explorative problem which students cannot solve without the right knowledge. After a brief struggling with the problem, an instruction explaining the missing concept is given. The approach engages students in active problem-solving, with the goal to increase the retention time of the theoretical concepts. We have developed our education around this using our in-house developed framework which includes lectures, workshops, and instruction videos facilitating the seamless integration of this approach into our own courses and to disseminate it among our academic peers [6]. To enhance the learning even more we want to introduce more experiments in our education and integrate this in our productive failure didactics.
UPE includes several modules and consists of weekly new subjects [7]. In week 1 students are "getting started", recalling all their knowledge on physics and maths from secondary school. In week 2 students are introduced to the rich world of materials where they are introduced to plastics, metals, and natural materials of which products are made. Next to material determination, students are introduced to several basic mechanical properties like yield and Young's modulus. In week 3 to 5 students are introduced to

internal loads and the beam theory, followed by internal loads and the normal, shear and bending moment diagrams. In week 6 will use this knowledge to calculate the internal stresses giving information whether a part will bend, sag, or break. In week 7 students are introduced to the manufacturing of parts from sheet metal bending to injection moulding, typically techniques focussing on plastics and metals. In week 8 we will finish the course with product architecture design, introducing them to SolidWorks, and joining techniques.

In the past years of the course these manufacturing techniques, like injection moulding, are taught theoretically using only textbooks like Ashby's "Materials and Design" [8] and its related software Ansys Granta Edupack. In this week students learn about attributes like tolerances, economic batch sizes, and design guidelines through lectures, books, and sometimes demonstrations or YouTube videos. This is mainly text-based theory, and practicing this knowledge in workshops is challenging. Experiential learning has a positive effect on learning and on retaining knowledge [9-13], and therefore we expect it will also help for students to make sensible choices about material-manufacturing techniques. To teach students the principles of common manufacturing techniques, we've introduced a simple machine that simulates injection moulding, thermoforming, and sheet metal bending (Figure 1).

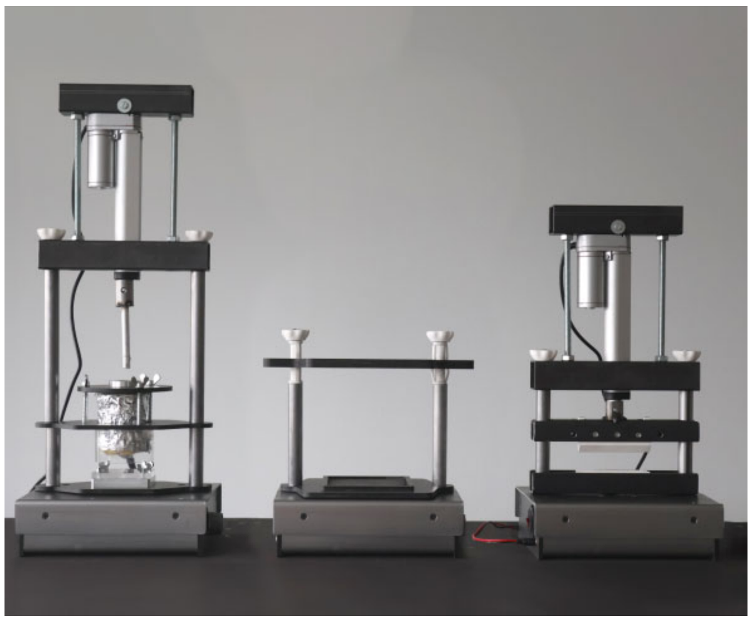

Figure 1. The experiential machine to experience from left to right: injection moulding, thermoforming, and sheet metal bending

More information about the machine can be found on the Autodesk Instructables webpage [14]. This machine is small, desktop-friendly, safe to use, and encourages experimentation. Especially in the first part of PF, where students generate and explore multiple solutions, this machine is invaluable. Students can use it to explore manufacturing techniques through experiencing the technique, relying on their prior knowledge. This hands-on experience often connects with what they already know, enriching the exploration phase. After this, they are more open to new knowledge, and we continue with the standard PF process of instructing and testing.

This machine was developed as part of a graduation project [15]. One requirement was that the machine should teach the basic principles using the PF approach and to compare this approach with a more traditional direct instruction method [16], we conducted an A/B test where 18 students were tested on their knowledge on thermoforming after (A) a productive failure approach using the experiential machine, and (B) a direct instruction on thermoforming. We want to know how the Experiential Manufacturing Machine (EMM) integrated in a productive failure workshop compares to conventional learning without Experiential Machine within the same timeframe.

2 APPROACHES

To test the impact of the EMM on deeper conceptual understanding and knowledge retention compared to conventional education via the use of the experiential machine is more effective compared to a direct instruction we have conducted an A/B test parallel to the general course where the machines are not yet used. We have introduced 18 students to the same materials. In this test 9 students were introduced to thermoforming following the PF approach, group A, where they use and struggle with the machine before watching the same instructional video and its related reading materials (figure 2). The other 9 students in group B were instructed through the instructional video and an educational text from "basisboek productietechniek" [17].

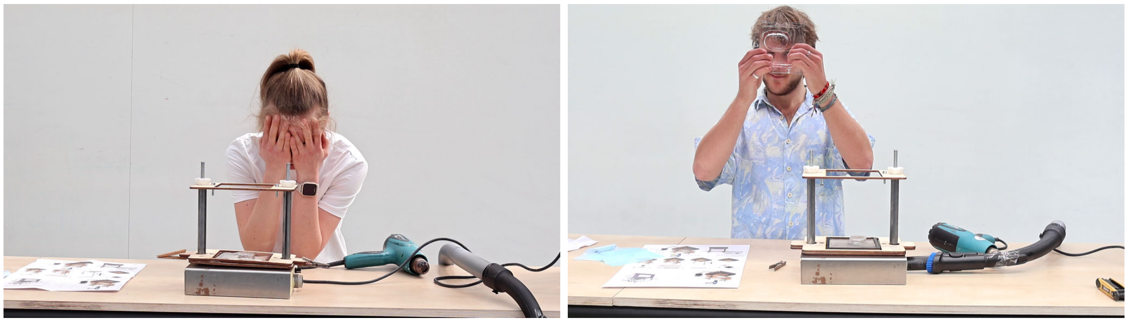

Figure 2. Two students experimenting with the thermoforming machines. Left, the student realises it had to connect the vacuum cleaner's hose to make the process work. Right, a successful realisation of a part using thermoforming

Both groups were given the same amount of time to absorb the knowledge before they were interviewed after the process of knowledge retainment. One week later all students were tested via an online questionnaire. Figure 3 shows the process both groups went through in this test.

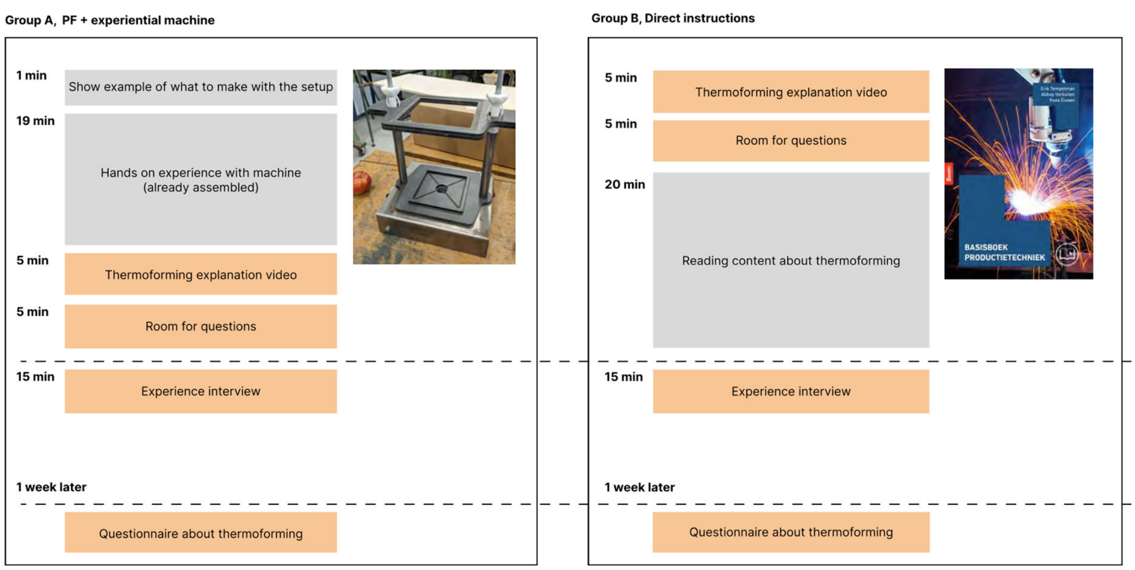

Figure 3. The process of both groups A and B went through to acquire the knowledge on thermoforming

The participants in this study included 18 bachelor students from TU Delft, equally divided between group A and group B. Approximately 50% of the participants were Industrial Design Engineering students and the remaining 50% came from various other faculties such as Mechanical Engineering and Technology, Policy and Management, with the distribution evenly spread across both groups. The gender distribution was random. Recruitment was conducted through the cohort's WhatsApp groups and personal connections. All selected students were unfamiliar with the thermoforming manufacturing technique. To stimulate serious participation, all participants are asked to complete the questionnaire with their best intentions and focus. To support their participation, they all received a 20-euro voucher at the end of the research. Informed consent was obtained from all participants prior to the study. Students are provided with a part that must be replicated and the assembled experiential machine, so the setup is pre-assembled, and students must only execute the forming step.

All participants had 30 minutes instructions on thermoforming. Group A followed a workshop with the productive failure approach integrated with the designed experiential learning machine. Group B follows the workshop with a direct instruction and self-guided book approach. All participants work independently, limiting influence from fellow students and group dynamics. Group A first experienced the machine for about 20 minutes after which they were given the same explanation video as which group B started out with.

After the educational part, all students were questioned about their experience using a structured interview that was based on experience questions [18] using a 5-point Likert scale. The following questions were asked:

1. Did you feel involved in the learning method?
2. Did you find it intriguing or fascinating to learn?
3. Did you become enthusiastic about the learning method?
4. How user-friendly was the learning method?
5. How confident are you to apply thermoforming?

To test the (short-term) retention about thermoforming, one-week later students were quizzed using an online questionnaire consisting of user-related questions, 7 content-based questions, and one question about their confidence on designing parts using the thermoforming process. Amongst others, the following content-based questions were asked:

1. Q1, Q2, Q3 producibility: the participants were shown three cross-sectioned parts and asked to indicate to what extent the cross-sections of these thermoformed products can be precisely produced.
2. Q4 products: the participants were shown four products (a chocolate inlay, a hamburger packaging, a stainless-steel metal tray, and a PET bottle) and asked to indicate which products can be made by means of thermoforming.
3. Q5 statements: shows the participants 5 statements on thermoforming and ask to indicate which of the statements are correct.
4. Q6 mould design: shows three types of moulds and asked about the type of mould most often used in thermoforming.
5. Q7 context: shows a picture of a moped-scooter windshield and ask the participant to choose a manufacturing process (injection moulding, extrusion, thermoforming or different) when the quantity is up to 100,000 pieces.

3 RESULTS

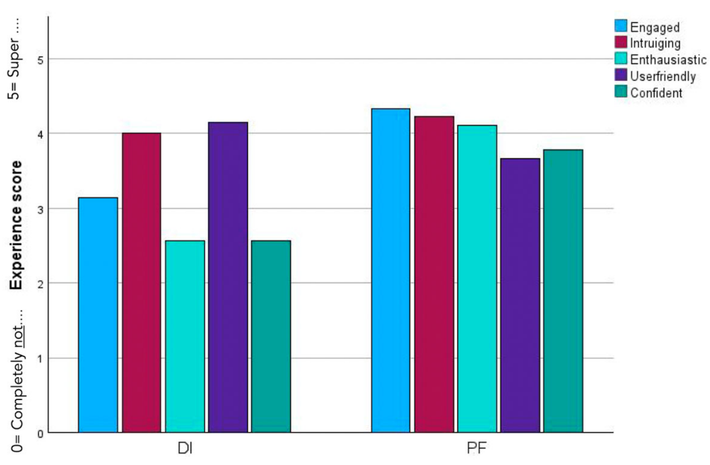

Figure 4. Results of the experience test

The results of students' perception/experience are shown in figure 4 and show that there is a significant difference in how students experience the different approaches. Students using the experiential machines (group A) felt more confident, enthusiastic, intrigued, and engaged compared to those using the direct instruction approach (group B). Only the user-friendliness was scored lower for the PF approach using the experiential machines. It must be noted that the standard deviation on the last question about their self-confidence for group A was very high. In the interviews and the experiences of students we observed there is a greater variety in responses within the experiential group (group A). Some students felt highly confident after using this method, while others did not. This pattern was consistent across almost all statements. Observations during the tests confirmed this, as some students struggled to proceed and solve problems without external assistance.

The content-based quiz is shown in figure 5 and show that there are some differences in the scores for both groups. Q5 and Q7 were answered better by students which followed the direct instruction approach (group B), whereas the PF approach (group A) scored slightly better on Q1and Q6 and significantly better at Q4. On average both groups score equally on content.

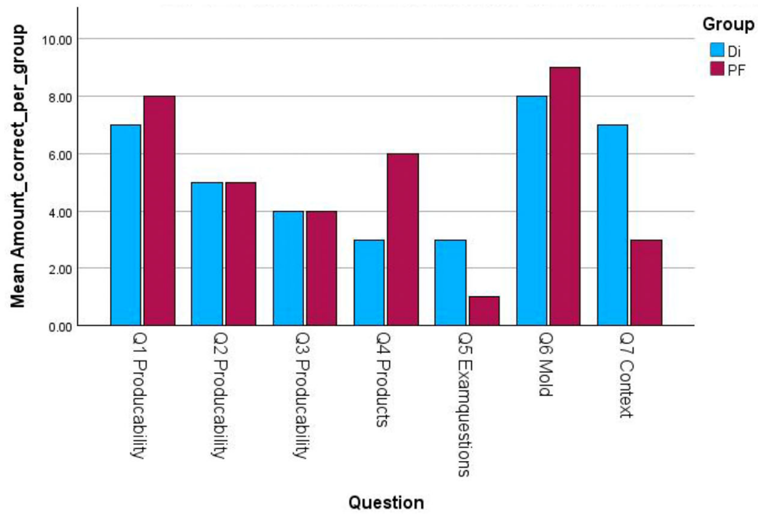

Figure 5. Mean score for the 7 different questions

4 CONCLUSIONS

The findings reveal notable differences in student perceptions and learning experiences. Students who used the experiential machines (group A) reported feeling more confident, enthusiastic, intrigued, and engaged compared to those who followed the direct instruction approach (group B). Despite these positive effects on learners' attitudes, the test results showed no significant differences in scores between the two approaches.

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After the content quiz, we found no significant differences between both approaches. Both groups have equal short-term retention and score as good on the quiz questions. This is consistent to the research of Kapur [10] and relates to the research of Chowrira et al. [19] which state that "[…] the addition of hands-on experiences helped them acquire basic tools with which they could make meaning of subsequent instruction". The only difference can be noted in Q4 where group A scored significantly better, and Q5 and Q7 where group B scored significantly better. This is likely because the book contains more examples of the applicability of the thermoforming process which were referred to in Q5. This broader context also led to some confusion in the question which asks which products can be made using a particular production process, that resulted in a higher percentage of correct answers for group A, the PF group.

During this test, we found that experiencing manufacturing techniques positively affects students' confidence in their ability to apply the technique. However, this does not necessarily mean that the students are more knowledgeable. As follow up of this research, long term research with larger sample sizes will be conducted and these might reveal more significant results.

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REFERENCES
[1] Industrial Design Engineering (2022). Discover the IDE Bachelor. Website visited March 1, 2022: https://www.tudelft.nl/en/ide/education/bsc-industrial-design-engineering/programme.
[2] Flipsen B., Persaud S. and van Breemen E. (2024). Enhancing retention in mechanics through the implementation of productive failure didactics, *E&PDE 2024*, 5-6 September, Aston University, Birmingham, United Kingdom.
[3] Kapur M. (2008). Productive failure. *Cognition and Instruction*, 26, 379–424.
[4] Kapur M. and Bielaczyc K. (2012). Designing for Productive Failure. *Journal of the Learning Sciences*, 21:1, 45–83.
[5] Persaud S., Flipsen B. and Thomassen E. (2022). Productive Failure in Action, *E&PDE 2022*, 8-9 September, London South Bank University, London.
[6] Persaud S. and Flipsen B. (2023). Productive Failure Pedagogy in Engineering Mechanics, *E&PDE 2023*, 7-8 September, Elisava University, School of Design and Engineering, Barcelona.
[7] Flipsen S. F. J. and Spek D. (2021). Understanding Product Engineering, Syllabus IOB1-2.
[8] Ashby M. and Johnson K. (2014). Materials and Design, the Art of Science and Material Selection in Product Design. Third Ed. Elsevier.
[9] Kolb D. and Kolb A. (2017). The Experiential Educator: Principles and Practices of Experiential Learning, Experienced Based Learning Systems, Kaunakakai, HAWAII.
[10] Kapur M. (2024). Productive Failure: Unlocking Deeper Learning Through the Science of Failing, Jossey-Bass.
[11] Morano M. F., Melo A. E. and Jarman A. (2021). Learning by making: A framework to revisit practices in a constructionist learning environment, *British Journal of Education Technology*, 52:3, 1093–1115.
[12] Backmann G. and Krause D. (2010). Improving the Mechanical Design Education by Hands-on Experience with Machine Parts, *E&PDE 2010*, 2-3 September, Trondheim, Norway.
[13] Li H., Öchsner H. and Hall W. (2019) Application of experiential learning to improve student engagement and experience in a mechanical engineering course. *European Journal of Engineering Education*, 44:3, 283-293.
[14] Taen R. (2024). Experiential Manufacturing Machines for Education, published on: Autodesk Instructables, https://edu.nl/qfvqp [accessed March 3, 2025].
[15] Taen R. (2024). Experiential Manufacturing Machines, master thesis. *Industrial Design Engineering*, Delft University of Technology, website: https://resolver.tudelft.nl/uuid:a8648cc6-e3b4-4a37-9836-2dae22adab09 [accessed March 3, 2025].
[16] 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.
[17] Tempelman E., Verkuilen A. and Eissen K. (2023). Basisboek Productietechniek, Boom Hoger Onderwijs, the Netherlands.
[18] Timur B. and Tasar M. F. (2011). In-service science teachers’ technological pedagogical content knowledge confidences and views about technology-rich environments. *CEPS Journal*, 1(4), 11–25. https://doi.org/10.26529/cepsj.403.
[19] Chowrira S. G., Smith K. M., Dubois P. J. and Roll I. (2019). DIY productive failure: boosting performance in a large undergraduate biology course, *NPJ Science of Learning*, 4:1.
[20] Persaud S. M. (2022). Productive Failure for Engineers: Embracing Mistakes in Engineering Education, available: https://www.tudelft.nl/teachingacademy/colleagues-in-the-community/education-fellows [Accessed on 2025, 19 February].