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PRODUCTIVE FAILURE IN ACTION

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ABSTRACT
In September 2021 the faculty of Industrial Design Engineering has implemented a completely revised bachelor. Important differences between the old and the new bachelor are its focus on design for higher complexity, the teacher as a coach, and the need for students to learn in an autonomous way. Within the bachelor, first year engineering students are introduced to the world of physical embodiment of products. This includes materials and design, manufacturing techniques, functional analysis, product architecture and mechanics modelling. In the past years we used a classical approach in teaching mechanics of materials using direct instructions and problem-based learning as the learning approach. Unfortunately, many design coaches observed that the acquired engineering knowledge was applied superficially or even left out of scope in students' design projects.
The complete overhaul of the bachelor and the seemingly short retention of topics related to product engineering, made us change our learning approach from Direct Instruction to Productive Failure (PF). Making mistakes is an important condition for learning, and Productive Failure incorporates this while promoting autonomous learning. In essence, Productive Failure is a method that fosters effective learning and fits very well with a general design approach of iterative and explorative learning.
During the development of UPE, we designed several workshops in a PF kind of fashion and applied it in the 2021 course. During the run we came across several hurdles in teaching, related to workshop design, and the impact of changing learning culture, and the teachers' role. This paper will discuss our findings when applying Productive Failure in our own class which is used to improve the course and line up the educational team in becoming productive-failure teachers.

Keywords: Product engineering, autonomous learning, productive failure, direct instruction

1 INTRODUCTION
In September 2021 the new bachelor revision is implemented at the faculty of Industrial Design Engineering. In this new bachelor's programme, more than 335 first-year students start their journey of becoming a professional designer. Based on the changes in the industrial design profession the curriculum has changed, and currently consists of courses in the field of technology, organizations and people, and is extended with new courses in the field of data, digital interfaces, and understanding values [1]. The approach within the new bachelor also shifted, and students are now always designing in semester-long design courses, and apply theory and skills educated in parallel theoretical courses. We also promote an inquisitive and eager learning attitude, where students learn more autonomously, where students are encouraged to take responsibility for their own learning and development. The autonomous learning approach does not only involve students to change their way of learning, but also demands a different teaching approach for all staff members involved. Teachers must make the transfer from being an instructor towards a facilitator, coaching students in their learning process.
For decades, the Faculty of Industrial Design Engineering (IDE) has taught mechanics in classical ways. Students are introduced to different topics on a weekly basis and practice the taught theory at home with book exercises and during workshops with guided direct instructions [2]. This is often intensive, as it is not only about knowledge transfer but more about understanding, the penny must drop. Over the years we observed that students apply their engineering knowledge superficially in design projects, or even leave them out of scope completely. Either the students forget about the knowledge taught, or they are not confident to apply it successfully, scared to make mistakes and therefore hesitant to apply engineering in their projects. Students experience technology as difficult, which means that some students drop out quickly. We see that Direct Instruction does not lead to self-study, except when the exam deadline is approaching. Unfortunately, it also appears that the knowledge does not retain, because

the practical application of the theory can be found sporadically in many following-up design projects, such as the bachelor's capstone project. Little is substantiated with mathematics, force calculations, materials science, and the use of engineering software. Our experience is that with this way of learning the material does not stick and that in many cases it does not become a sustainable part of the set of competences.

After finishing secondary school, Understanding Product Engineering (UPE) is one of the first courses where students are confronted with autonomous learning. While developing UPE, we investigated multiple teaching approaches which could spark an inquisitive learning attitude, make knowledge stick longer, and which fits with a designerly-way of learning as described in the Kolb experiential learning cycle [3]. Academic designers have in general a trial-and-error approach, where the Kolb cycle is commonly used to experience, fail, reflect, learn, and improve. The goal is to motivate students in exploring the physical embodiment design-space and preparing them for a curious life-long learning. Productive Failure (PF) came across as a theory that incorporates experiential learning, where learning from mistakes promotes autonomous learning. In essence, Productive Failure is a method that fosters effective learning and fits very well with a general design approach of iterative and explorative learning [4].

The productive failure theory and method is new and unknown to both our students and our teaching team. Within this paper we want to investigate how we can effectively apply PF in UPE, which techniques work, and how we can train and help our team of teachers to change their ingrained ways of lecturing. Based on existing literature PF works well with small number of students, but when applied to a larger number of students with a larger team of educators, seams not been investigated. This paper will discuss our first experiences when applying Productive Failure in a larger design course where the complete teaching staff has to make the transfer from Direct Instructions and Problem Based Learning to Productive Failure. First, we will discuss the productive failure approach which is used as a basis for autonomous and life-long learning, followed by a description of the developed course, Understanding Product Engineering. We will discuss the weekly designed activities and the hurdles we came across when applying PF in the course, both from a student's perspective and that of the teaching staff. We will finalize the paper with a reflection on our learnings and concluding remarks [4].

2 PRODUCTIVE FAILURES

In the coming years we want to work less with Direct Instruction (DI) in our pedagogical approach and make more use of the Productive Failure (PF) approach [5]. Productive Failure is a teaching method where designed guidance in the initial learning is proven to be more effective than guided direct instructions and problem solving, which is less intensive than Problem Based Learning. The method has proven that students who engage in problem solving prior to instruction, demonstrate better performance on conceptual understanding than those who engage in problem solving after instruction [6]. It is also found to be less efficient, but on the longer term it sticks better and appears to be more effective. In essence, the student experiences a certain situation, reflects on his actions, searches for the theory and applies it within the context.

The method consists of two phases: (i) generation and exploration and (ii) consolidation. In the first phase, students solve an unguided problem and engage in a targeted concept, using prior knowledge to generate or discover suboptimal or incorrect solutions (the failures). The nature of these solutions provides teachers and students valuable insights into the types of knowledge that was activated and how this knowledge is relevant in relation to the targeted concept. In the consolidation phase students use relevant solutions to turn them into ‘canonical solutions’ [7] like stepwise approaches solving mechanics problems. This provides opportunities for students to notice the inconsistencies in their prior knowledge and realize their current limits. It supports students to attend to and better encode critical features of the new concept while comparing the student-generated solutions with the correct (instructed) solutions. So, it provides opportunities for teachers to formatively assess the progress of the students by having a dialogue with the students on the right and wrong approaches of problem solving. An important affective benefit of this approach is greater engagement and motivation to learn the targeted concept [7]. To design a course using PF several guiding rules are to be followed [8], for both the Generation and Exploration phase, and the Consolidation phase.

3 UNDERSTANDING PRODUCT ENGINEERING

In 2018 our course-development team has been commissioned to develop a course which merges knowledge from multiple courses in the previous curriculum - Statics (7.5EC), Engineering for Design (7.5EC), and Manufacturing & Design (7.5EC) - to one introductory course of 5EC. This demands a complete overhaul of teaching engineering design where the basic knowledge of mechanics, materials and manufacturing must be taught in a very short period and with fewer contact hours, demanding more self-study, a higher intrinsic motivation and student's autonomy. Within the developed course of Understanding Product Engineering (UPE) we introduce our students to the world of physical embodiment of products where we use the engineering wheel as a metaphor for product engineering design (Figure 1). In the course five major aspects of embodiment design are considered: modelling of mechanics (loads and statics, "Belasting"), product and part functionality ("Functie"), materials and their performance ("Materialen"), manufacturing and assembly ("Productie"), and product architecture ("Opbouw").

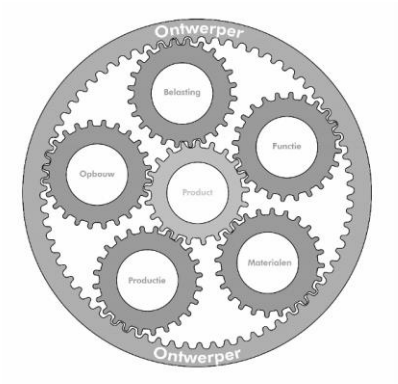

Figure 1. The five aspects (loads, function, materials, manufacturing, and product architecture) of Product Engineering as taught in UPE

During the development of UPE, we designed several workshops following the PF design rules as stated before [8] and applied them in the 2021-2022 course. The year started out with 335 first-year students. Within the course we use a weekly rhythm of online Monday-morning lectures, and on-campus Wednesday-afternoon workshops, where the lecture consists of three parts:

1. A reflection on last-week's learnings and clarifications of unclear topics.
2. Introduction to the topic-of-the-week, the needed content and where to find it.
3. An outlook on the upcoming Wednesday workshop and the student' preparations every student should carry out.

Figure 2. Left, collaborative learning solving engineering problems using the whiteboard; Right, experiencing mechanics using a hammock construction

The workshops are in a studio setting with a maximum of 30 students per classroom, where students collaborate in groups of 5 to 6 students working on the topic-of-the-week, solving engineering problems together and experiencing mechanics (Figure 2), and experimenting with real-live test-setups and product autopsies (Figure 3).

The course consists of 8 weeks of knowledge acquisition, one week of exam preparation and the final paper exam. The course's development team consisted of three experienced lecturers in the field of product architecture, materials and manufacturing, and mechanics, assisted by two teaching assistants. The team prepared the content using constructive alignment, where learning objectives, feedback and assessment, and the learning activities are aligned [9]. The team developed a general approach consisting of weekly learning objectives, and learning activities, using relevant literature bundled in a reader [10] and two books [11,12]. The course was designed in such a way that both the bachelor revision requirements (autonomous learning, formative assessment and teacher as a coach) and the guiding rules for applying PF were satisfied.

In preparation for the course, the teacher needs to get acquainted with the new bachelor vision, UPE and PF. For this we organized a session where the course design team presented the integration of these three elements prior to the start of the course. In this lecture-session, the teaching staff discussed the content of the course, the workshop setup and elements of PF. Teachers shared their previous experiences of other courses and it served as a social bonding moment.

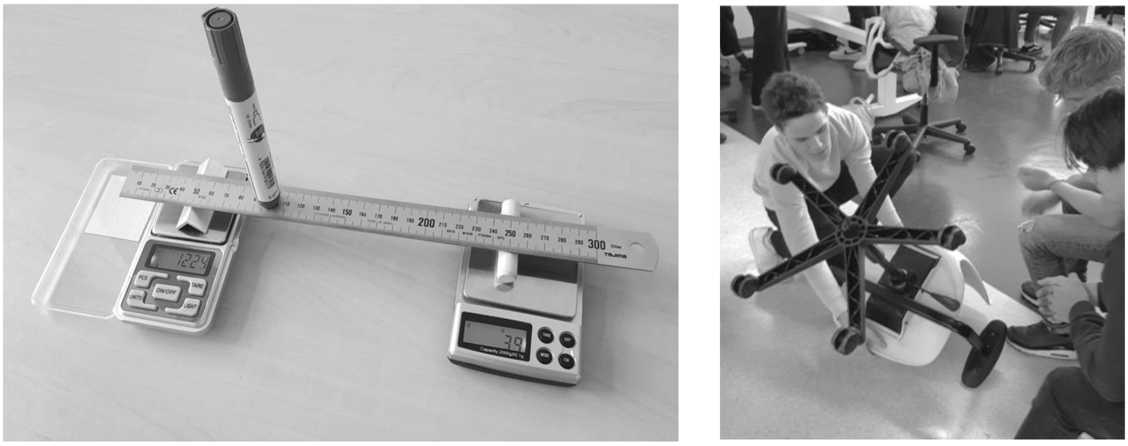

Figure 3. Left, experiential learning by measuring the reaction forces and comparing them with the calculated outcome; Right, product autopsy, analysing an office chair on materials and manufacturing

4 RESULTS WHEN RUNNING THE COURSE

During the implementation of PF in our new course we stumbled upon several hurdles. We experienced three phases in applying PF: (i) week 1 to 3, where we made our *first steps* in PF applied in the course; (ii) week 4 to 6, where we learned how to apply PF in the right manner, *getting it right*; and (iii) week 7 to 9 where the students' urge for direct instruction became stronger than applying PF in the course, the *exam preparations* phase. Underneath these three phases are discussed further and conclusions are drawn.

4.1 First steps

The first three weeks were varying in success. Students were in their first week at university not knowing the culture and whereabouts at the faculty. We observed that most students and teachers struggled with autonomous learning. From secondary school, the most common way of learning had been Direct Instruction. Students did not start working on the workshops, waiting for teachers to instruct step by step what to do. Finding the "sweet spot" did not work well yet. Retrieving their prior knowledge on mathematics and physics turned out to be a struggle, many students could not recall basic calculations and concepts.

Besides struggles in autonomous learning, the formative aspect did not come across. Most students wanted to know if their answers were correct and found it very difficult to explore with minimal guidance. The strong urge to have correct answers and getting the workshop done frustrated both the teachers as the students. These elements combined with not knowing each other very well yet, made it quite difficult for teachers to create a safe space.

Collaborations in smaller studio groups of 5 to 6 students using the whiteboard and sharing the results to other groups via a Miro board went quite well and supported sharing representations and solution methods.

4.2 Getting it right

Each week prior to the workshop, the teachers reflected on the integration of the renewed bachelor requirements, the content of UPE, and the implementation of PF in the course. With guided dialogues, the team of teachers became a safe space for expressing concerns but also ideas on for instance, different coaching techniques, the use of different resources, different levels of understanding, and different levels of engagement. It became clear with doing the first run of the course, the teacher team was also in a "productive failure" development.

In week 3 the workshop was grounded in the Experiential Learning Cycle (ELC) [3]. The teachers were provided with an in-depth lecture of ELC. It provided clarity and guidance for students and teachers. In this week students investigated a hammock (figure 2, right) which engaged students in experiencing forces, and mechanics of materials. Students collaborated in data collection, started retrieving knowledge from the first two weeks and collaborate in whiteboard calculation. This approach should lead to collaborative forming of the canonical concept of tensile forces substantiated with algebraic equations. Unfortunately, figuring out these concepts did not work out due to the limited time available.

The workshop of week 4 can be considered as the first time we found the "sweet spot". The workshop had a clear time frame, where the first hour was spent on a recap of the previous week and an exercise using their previous knowledge on statics. In the first hour students address a bending beam and had a choice in methods to calculate and produce normal, shear, and bending diagrams (e.g., by hand calculations and CAS software, online visual tools like BeamDesign and STRAIN, and physical prototypes using Fisher Technik). The teacher walked around the classroom, not providing answers, only asking questions to promote solution finding. During the second hour students had to apply their learnings to a real product they brought from home. Solutions were shared via an online Miro-board and both the groups and teacher reflected on the result within the studio during the third hour of the workshop. The remainder of the workshop, students were provided with the step-by-step method, guided by the teacher who attended each student group individually.

At the beginning of week 5, some teachers still found it difficult to make their classroom a safe enough space. To address this need, we organized a lecture about how to create safe classrooms to support the first stage of PF. While executing the tips, teachers visited each other's classrooms to provide valuable feedback for improvement if needed and discussed their coaching during the coffee breaks. The "sweet spot" of the workshop set up could be continued from week 4 to week 6. Only the topic changed but the workshop setup remained the same and was successful.

4.3 Exam preparations

During week 7 our students noticed the final exam getting closer. Their focus shifted from needing to know new concepts to being able to pass the exam. The need to have exam training and correct answers promoted higher stress for our students. This state of being made it impossible to work in an unguided explorative manner as defined in the first phase of PF. To support the wellbeing of our students, we decided to transform the workshops into instruction-based exam preparation. We additionally organized Q&A sessions, to comfort and increase the confidence of our students on their abilities.

5 DISCUSSION AND CONCLUSIONS

We have developed a new course using PF as an approach to promote inquisitive, autonomous and life-long learning. This is done by designing activities in such a way that students solve an unguided problem and engage in a targeted concept, using only prior knowledge, generating suboptimal or incorrect solutions. In collaboration with the coaches these "failures" are used to provide insights into the current student's lack of knowledge (need to know) and guide them using the relevant solutions as instructed by the teachers. With this approach, we expected more motivated students and teachers who enjoy practicing technology, with more courage to make mistakes and thus continue life-long learning.

The course development team applied PF design rules in producing the relevant workshop activities, but both the students and the teaching staff came across several issues during execution. The teaching staff and the students had to unlearn old, and often ingrained habits and become accustomed to the new learning culture. Generally, our student and teacher population are used to instructed teaching, and during the first three weeks both found it difficult to transfer from the ingrained instruction-based learning to a more autonomous learning. The first phase of PF prescribes the student's need to "generate and explore multiple representations and solution methods" of the theory. The workshops were set up freely and too general, and students took too much time to go through the exercises. Students kept on requesting instructions and solutions to the presented problems, and the teaching staff did not know how to deal with these requests conflicted with the promoted autonomous learning. Clearly students find it hard to take autonomy, but also teachers find it hard to give. Within the first three workshops we never achieved phase two of PF where the “discoveries are linked to the theory”.

In our own “failing” of transitioning to phase two of PF we changed the setup stimulating collaboration between students (e.g., by using the whiteboard to solve problems) and set a clear timeframe consisting of an exploration and consolidation phase (phase 1 and 2 of PF). This renewed structure kept students away from struggling through, getting frustrated, and running out of time. In week 4 we first found the “sweet spot”. We learned that the educational team needs to switch roles during the workshop from facilitator in during the exploration phase of the workshop to an instructor in consolidation phase. The timeframe helped the teaching staff knowing when to switch roles. .

To facilitate collaboration and create a safe space for the teaching staff we collaborated with all members of the educational team and (re)designing the workshop structure and activities together. During weekly staff meetings we elaborated on the content and the workshop structure. Creating a safe space in the studio environment was found to be very important to connect with the students and work in the same playing field. We therefore discussed creating a safe space by increasing mutual student-teacher respect and trust by dialogue and positive coaching techniques. We organised a lecture on creating safe classrooms and coaches visited each other’s classrooms to provide valuable peer feedback during regular coffee breaks.

In hindsight, we had prepared the workshops in a PF-kind of fashion and learned to do it better during the run of the course. In essence we also went through the process of productive failure. For the next run of the course, we propose the following approach to design a workshop. First, the course learning objectives must be dissected into related *concepts* students need the learn. Second, these concepts need to be related to the student’s prior knowledge, and the *blind spot* (knowledge gap or misconception) must be defined. The exercise for the week’s workshop should be designed around this blind spot. Students will work on the exercise and fail, after which they are introduced to their misconceptions and learn the new concept. A safe space to experiment and make mistakes, together with a clear timeframe are key to successful learning.

Transforming from an instructive teaching culture to a more autonomous learning environment demands some changes in the teaching and learning culture. During the development and running of UPE we experienced that taking along the complete teaching staff in these changes is key. It is impossible to make this culture shift in one go, and therefore we also must fail productively.

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