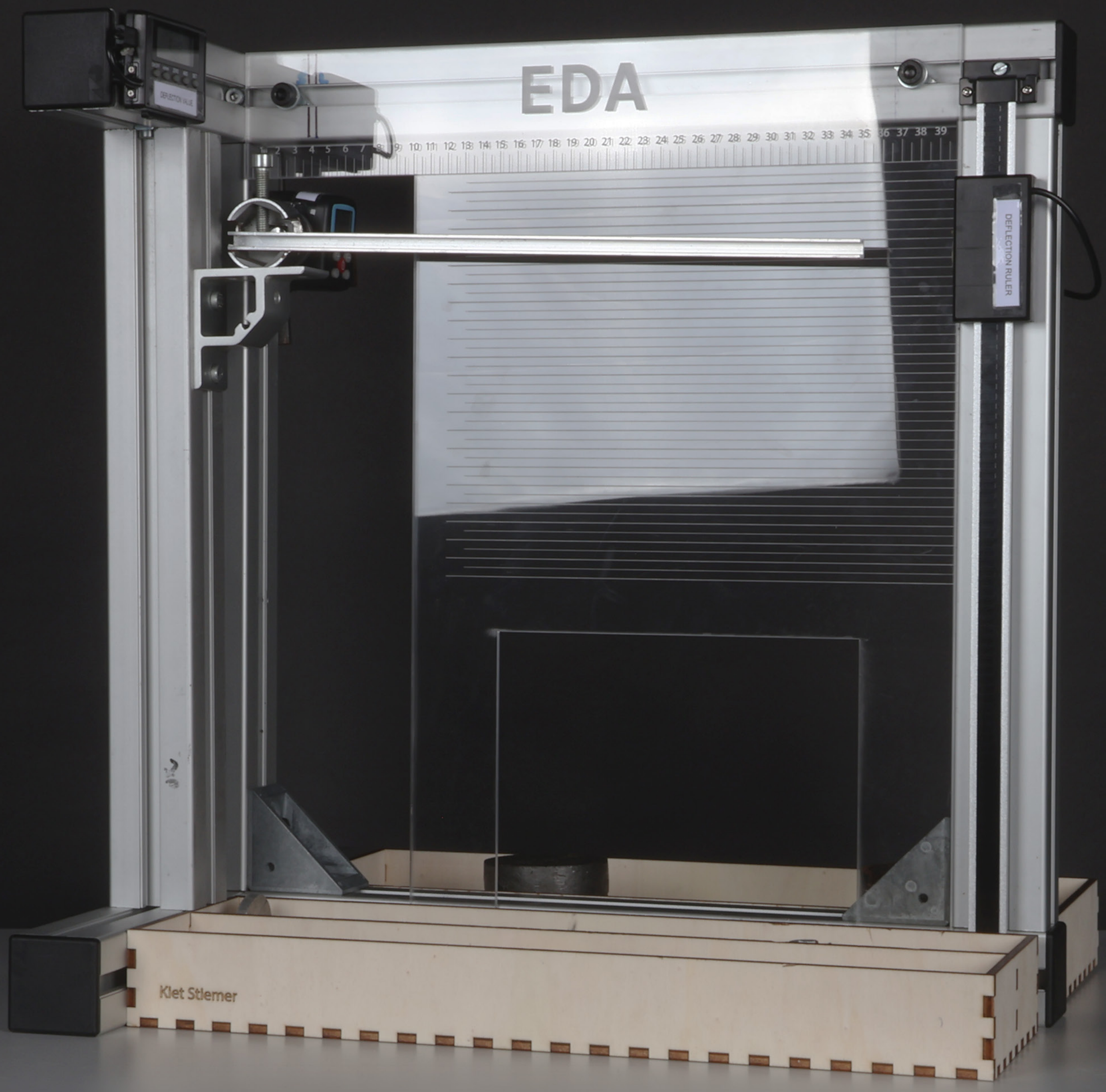
Educational Deflection Analyser

Improving mechanics education with an experiential machine



TU Delft - Industrial Design Engineering
Master thesis by K.G.C. Stiemer
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Executive summary

This graduation project explores the problem of teaching engineering education through the course Understanding Product Engineering (UPE) to first year bachelor students at the TU Delft faculty of Industrial Design Engineering, which is a significant issue in the context of the reduction of time allocated to technical subjects in the programme. Moreover, students are not applying their engineering knowledge and skills in their design projects, possibly meaning the way it is educated is not effective. The primary goal of this research is to design an *experiential machine*, aiming to address the lack of practical, hands-on learning experiences in early engineering education through the development of a prototype and accompanying educational module. This is guided by the Productive Failure learning approach.

The project began with an initial exploration phase, where the different subjects of UPE were explored, a questionnaire was conducted and literature was reviewed to understand the end users' needs and how to effectively teach subjects. From this, several key findings emerged, including the choice of direction for statics with a focus on beam bending. Additionally, it was discovered that teaching relies heavily on the way motivation in students is created.

Based on these insights, the next phase involved generating design concepts and developing a proof of concept for an experiential machine, guided by the requirements that followed from a deeper look into the subject of statics and beam bending. This concept phase culminated in the embodiment of the Educational Deflection Analyser (EDA), which was further refined through technical assessments and user tests.

To validate the design, two user tests were conducted, and the results indicated that the EDA is a functional proof-of-concept with the potential to engage students by sparking their curiosity to learn something new. Despite requiring some future iterations concerning the usability and full integration in the educational context, the project successfully developed a setup to teach first year students the fundamentals of product engineering.

In conclusion, this report demonstrates that with continued development, the EDA holds the potential to become an effective learning tool in the future to make engineering education enjoyable and see the application reflected in design projects. Future work could focus on the improvement of the user-friendliness, elaborate evaluation and digital integration of the electronics.

Table of content

Introduction

This report is a master thesis by Kiet Stiemer, created under the faculty of Industrial Design Engineering (IDE) at the TU Delft during the master programme Integrated Product Design.

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1.1 Context

At the IDE faculty, the bachelor program Industrieel Ontwerpen is offered. During the first-year course Understanding Product Engineering (UPE) different basic engineering subjects are covered: basic maths, statics, NVM lines (normal-, shear force and bending moment), stress and strain, manufacturing techniques and product architecture. This used to be split up in three different courses spanning a total of 30 weeks, but due to revisions of the bachelor this has been condensed in a single 10 week course. This means the way the subjects are taught needs to be highly effective.

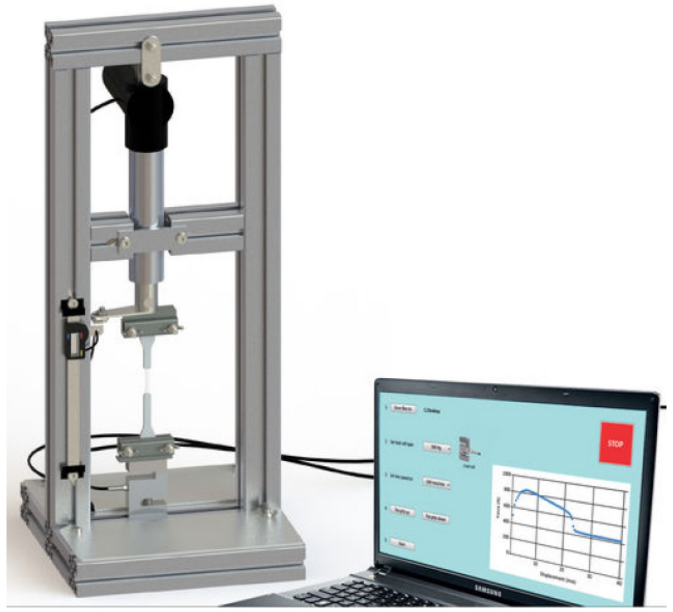


Figure 1: The LETT (Welling, 2014)

The course coordinators apply the Productive Failure (PF) approach (Kapur, 2008), in which they let 'experiential machines' play an important role. Experiential learning is based on a theory by David A. Kolb (Institute for Experiential Learning, 2023). Students are encouraged to try principles and methods out by themselves, during which things are allowed to go wrong. It is stimulated to learn from mistakes. For example, the Low Entry Tensile Tester (LETT) is used to teach about material properties and tension and compression (see Figure 1). The first year consists of 350 students and during this course they usually have an afternoon to use such a machine to get practical experience with the current week's topic.

1.2 Problem definition

Now, there is a lack of diversity in these experiential machines. The coordinators have evaluated the presence of UPE knowledge in the bachelor final project, by asking the project coaches to rate the presence in the reports they assessed (Persaud & Flipsen, 2024).

The results are shown in Figure 2. They conclude that the visible usage of engineering topics is very low, especially on the fundamental subjects like statics and internal stresses. This forms another reason for the wish of more experiential machines, as they hope these improve the students' retention over time and to see this reflected in the final project.

Mainly statics, manufacturing and product architecture lack a setup like the LETT. It is of great value that students can learn about these techniques in a hands-on way, as this stimulates the learning process. Especially the more abstract principles like statics are easier to understand when put into practice. Therefore the assignment is to design a new machine for any of those subjects, as stated in the original graduation project assignment (Appendix 1). The original, formulated assignment prior to starting this project is to *Create an experiential machine to improve the hands-on education in basic engineering principles for first year bachelor students* (Appendix 2).

Students can stare at a text book for hours and get a vague understanding, or spend one afternoon practising this theory and understand it way better. This will create value later in their studies or career, as however you slice it, they will encounter moments where their knowledge about basic principles helps them. Furthermore, engineering should be fun and attractive to beginning design engineers. Based on the Motivation Continuum by Visser (2017), it is crucial for students' motivation that their reason to take action is personal interest and excitement-driven. Engineering is often seen as difficult and students get demotivated quickly. The imagined experiential machines should spark more enthusiasm for the engineering side of IDE.

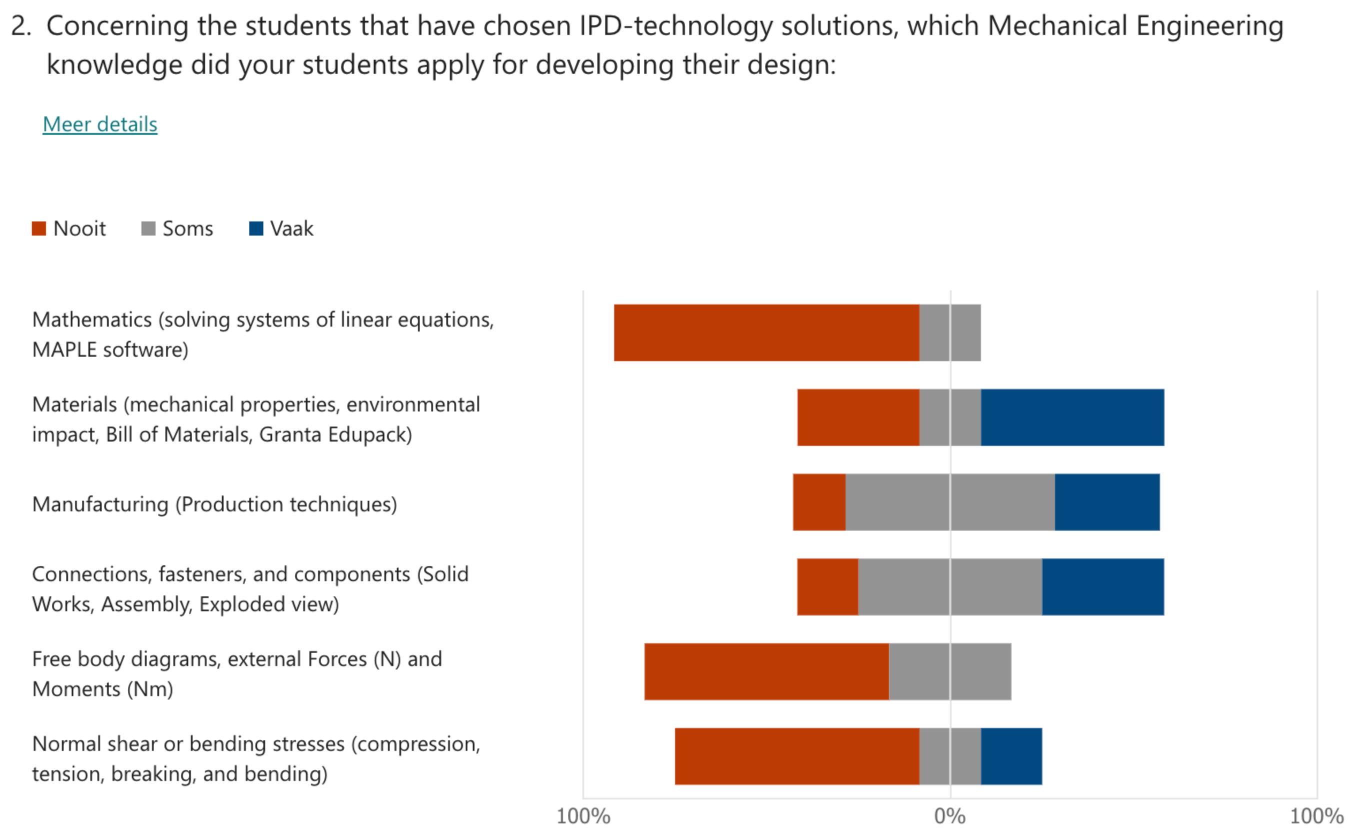


Figure 2: Different engineering topics applied in bachelor final project (Persaud & Flipsen, 2024)

The assignment requires the end product to be low-cost, as it might be produced 20 times so all first year students have access to it. Besides this, it should be possible to apply the Productive Failure approach with this machine, mainly meaning the way it is setup needs to allow for trial and error. If it is too perfect, students cannot make (valuable) mistakes. Lastly, the design should also come with an accompanying educational module that includes assignments.
The initial goals and basic design requirements that follow from the problem definition are summarised in Table 1. The requirements are expanded throughout the project.

Table 1: Initial design goals and basic requirements

Goal
Must have an accompanying educational module
The Productive Failure approach must be implemented in the design and assignment module
Must offer a physical, hands-on experience
Must be scalable to 20 units
Cost must stay under €500
Users must acquire an improved understanding of the subject

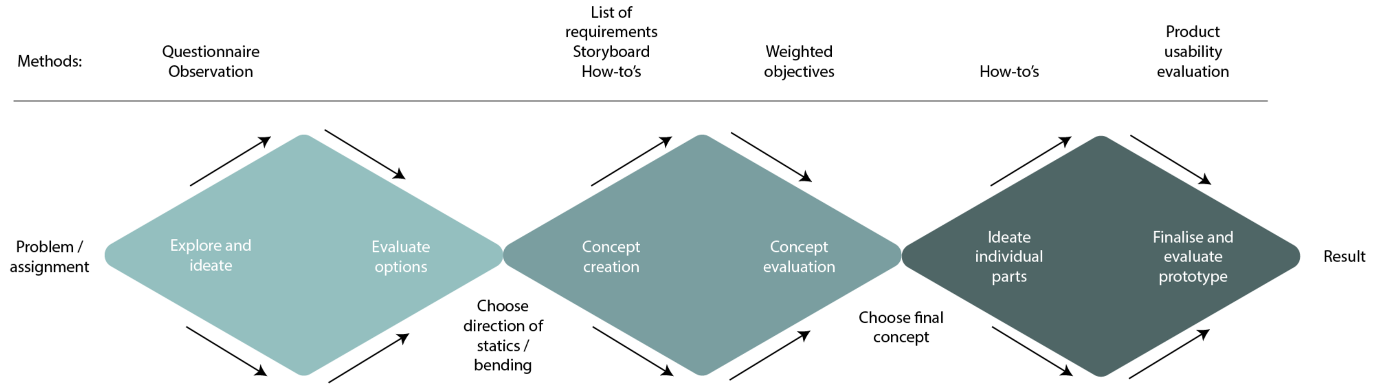


Figure 3: The Triple Diamond process of the graduation project

1.3 Methodology

During this project, the Triple Diamond method is used. This is an adaptation of the classic Double Diamond design method by Design Council (2005) that can effectively be used to communicate the design process of this project (Figure 3). In broad terms, this report follows the same structure. As shown, the direction that is chosen for the project is statics as subject. This will be discussed in chapter 4. Shown are also the design and research methods that are used in the specific phases of the project. Most methods are based on the Delft Design Guide or DDG (Van Boeijen, Daalhuizen, Zijlstra, & Van der Schoor, 2017).

2

Initial exploration

In this chapter, the problem space is explored. This is done by analysing the current situation and reviewing relevant literature. Simultaneously, first ideas are created, shown in the following chapter. This leads to a choice of direction, as the course UPE involves 7 different subjects, each of which has the potential to be improved with an experiential machine.

2.1 UPE

The course UPE covers seven subjects, which are shown in Figure 4 in chronological order. The UPE subjects can be divided into the more fundamental part of product engineering and the more advanced part. Maths, statics, materials and stress & strain are fundamental, where manufacturing and product architecture are about the application of the fundamentals.

Figure 4: Division of UPE subjects

The course is ten weeks and starts with subject one. Generally, one subject is covered each week. This are many subjects for the time span of the course and it is a consequence of the renewal of the bachelor programme. These subjects used to be taught during three different ten week courses, called Product Statics, Engineering for Design and Manufacturing and Design. Now, students need to learn the same subjects but simplified and in shorter time. They generally have half a day of lectures and half a day for a workshop. The goal of the workshop is to get familiar with the subject. To improve this, the IDE staff chooses to use the Productive Failure approach to these workshops. This is described and explored in a separate section (2.5).
The choice to teach these subjects derives from the way the bachelor programme is organised, which is by means of Final Attainment Levels (FAL's).

2.2 Education & regulation

The faculty works with FAL's, these are skills or knowledge that students should have acquired at the end of their bachelor. The FAL's are divided over the bachelor courses to make sure all levels are covered. The more technical ones are connected to courses like UPE, e.g.:

- Level 2.2.1 *Statics and dynamics* "Students are able to apply the basic principles of statics, mechanics and dynamics in product engineering"

- Level 2.2.2 *Materials and Manufacturing* "Students are able to apply knowledge of a variety of materials and manufacturing processes and the related opportunities and limitations for embodiment design"

From the FAL's, the LO's of the course are determined.
FAL 2.2.1 corresponds with
- 1.3 "Apply the basic principles of statics in product engineering including free body diagrams and equilibrium equations."

FAL 2.2.2 corresponds with
- 1.4 "Apply knowledge about the most common materials and manufacturing processes, and the associated possibilities and limitations for product design"
- 1.5 "Apply the basic principles of mechanics of materials and materials science in the most common construction situations within the context of product design"

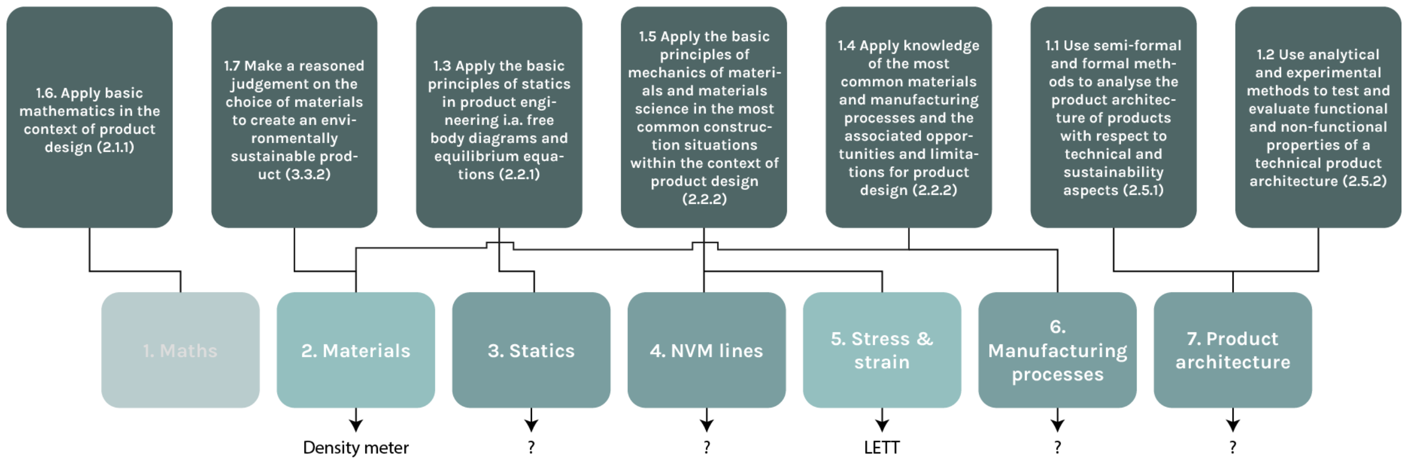


Figure 6: Opportunities for UPE subjects

The existing LETT machine fits the latter part of UPE. Mainly material from LO 1.5 is covered, as the LETT revolves around material properties like the Young's modulus and yield and tensile strength.
The different subjects and corresponding learning goals are organised in a diagram that is made in collaboration with Robin Taen. This diagram is used to identify design opportunities for the UPE subjects. In Appendix 3, the full version is presented. In the overview, the FAL's and LO's are categorised using the (revised) Bloom's Taxonomy (Anderson & Krathwohl, 2001). This is a way of categorising educational goals and objectives, among other assisting with structuring curricula. The six levels of Bloom are shown in Figure 5.

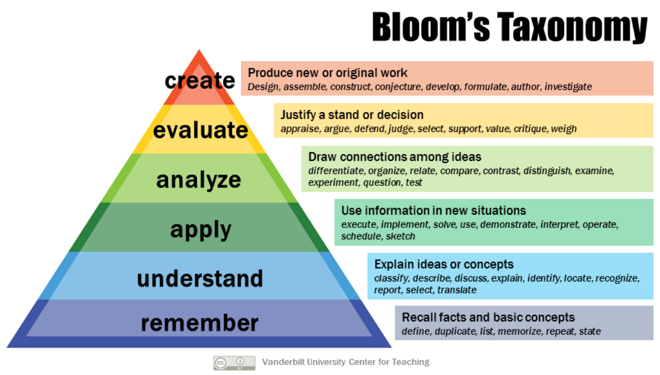


Figure 5: Bloom's Taxonomy levels (Armstrong, 2010)

The result of this analysis is summarised in the visual in Figure 6.

As can be seen, there are four subjects that lack any experiential machine, as Materials (2) has a setup that helps to find out the density of a material and Stress & Strain (5) has the LETT. The density setup is technically not an experiential machine, but as the other subjects have no setup, it is decided to focus on those. Maths (1) have been excluded, as the level that is taught is considerably low, therefore it does not seem a priority and is left out of scope. In the analysis, open-book UPE exams are also evaluated and questions categorised on Bloom's level. It becomes apparent that there are subjects that should be taught at a higher blooms level, like 'analyse' or 'evaluate', but sometimes the questions only go as far as 'remembering'. This is most likely attributable to a shortage of time in the course. That phenomenon is true for Manufacturing processes (6), as the exam questions are mostly to rate four statements about a pictured process on correct/false, while students can look this up in their book.

It also stands out that Product architecture (7) is not examined in most of the exams, and when it is, the difficulty of the question is very low level. This subject does therefore not seem to have a high priority.

2.3 Exploring student difficulties in UPE

To get further insight in the opportunities, the pitfalls that students encounter were explored. Together with Robin Taen, another graduate student with the same starting assignment, a questionnaire is conducted. The questionnaire has two parts: in the first part, the participants answer questions related to technical insight. The goal here is to identify what subjects are answered incorrectly the most. The second part is more generic and focused on their experience with UPE. Here the students can, amongst other things, indicate which part(s) of UPE were the hardest for them. Full results of the questionnaire are discussed in Appendix 5.

The questionnaire was filled in by 23 participants, of which some did not answer all questions due to a slight change to the questions halfway through carrying it out. The participants were all bachelor students except for one. From the participants, 87% finished the course UPE successfully.

2.3.1 Findings

The results give an indication of what students struggle the most with. Questions about manufacturing or related design insight fluctuate in response accuracy. Many people know what the body of a car is made of, but the large majority overestimates the thickness of the material by a large factor. It also is clear most people know injection moulding as a common plastic manufacturing process, but their knowledge does not go

further as they mistakenly identify a rotation moulded object for an injection moulded one. In a typical statics exercise, choosing the correct option may not be too difficult for students, but explaining why they made that choice is often more challenging. Many students forget that a force applied over a distance creates a moment. Despite this, their intuition often guides them to the right answer, even if they can't fully explain the reasoning behind it.
Choosing the correct orientation for an H or I beam under load is done incorrectly around one third of the time, possibly indicating a lack of understanding of where a load creates the largest stress and of moment of inertia.
Something else the participants seem to struggle a lot with is choosing the correct shear force and bending moment diagram for a given load situation. This also corresponds with what they indicate when asked what UPE subject they found the hardest (Figure 7). The top three are clearly the fundamentals of product engineering. When asked why they chose their answers, there is no clear reason that occurs most often. The answers range from abstraction and absence of preexisting knowledge for NVM lines to not getting enough time to internalise something.

2.3.2 Limitations

The questionnaire is a first tool to explore the problem space. Its execution is of value for the project, but as it is quite broad and quickly setup, fully scientific evaluation is complicated. As stated by (Van Boeijen, Daalhuizen, Zijlstra, & Van Der Schoor, 2017d), the quality of the results depend heavily on the quality of the questionnaire. If students answer questions correctly, depends a lot on the difficulty level of the question, which is determined by the questioners and only loosely-based on exam questions. This decision was made to ensure the questionnaire remained approachable and not overly challenging for participants. Additionally, keeping it concise helped prevent participants from becoming overwhelmed or stopping before completion.
The respondents were from different study years and in the analysis it was not checked if there was a performance difference between the cohorts. However, something similar is done by Persaud & Flipsen (2024) with a retention test concerning UPE.

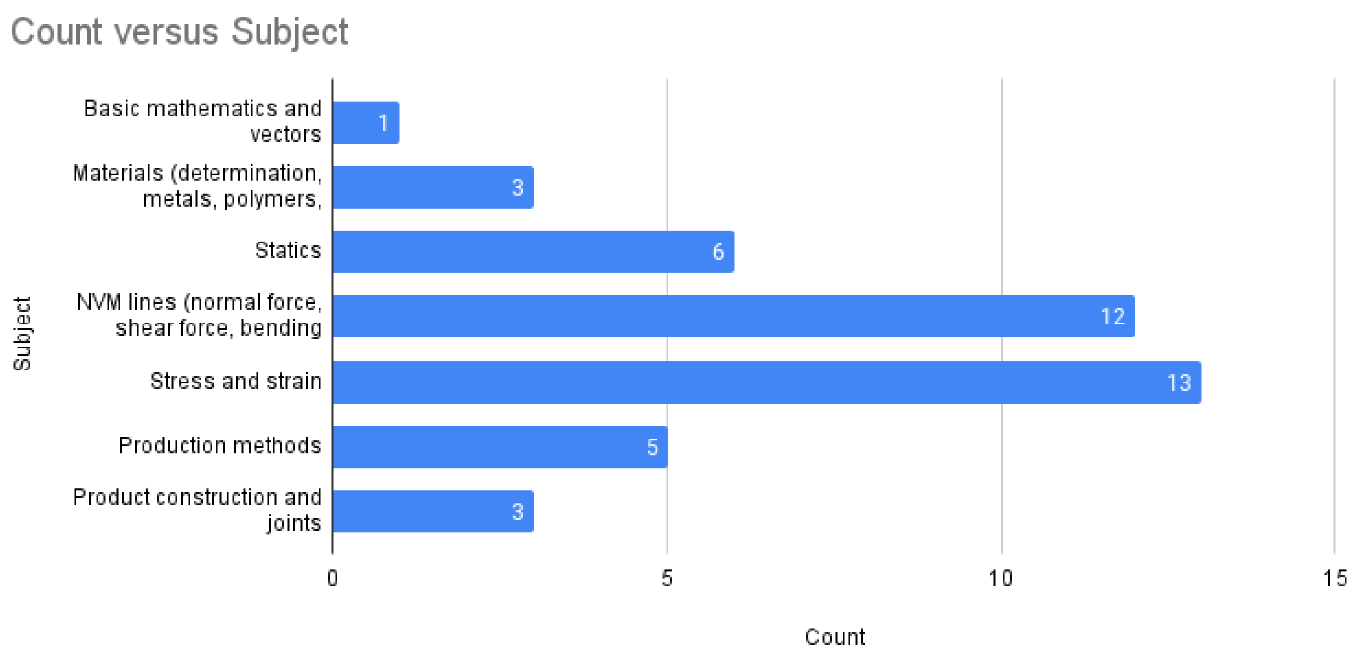


Figure 7: Amount of times participants (n=23) rank a specific subject to be difficult

2.4 Retention

In the mentioned paper, the researchers try to evaluate if their Productive Failure approach in UPE affects the retention of theoretical concepts. They do so by letting second year students perform a mini-exam during the first lecture of the engineering course Product Engineering (PE) and comparing the results over the years. In the results, it is clear retention reduces with each cohort, but no conclusions can be drawn as to what the effect of the PF approach is. The results do indicate the most recent cohort to be more confident in answering, as they do not answer "I don't know" as often as the other cohorts, even though the amount of wrong answers is similar.
This retention test will be done annually, so more data is gathered in the future. For this experiential machine project, there is potential to test if a group that uses such machine has better Retention Time than a group that was instructed with a traditional approach. If these experiential machines get implemented in the course, this could perhaps lead to improved retention in the cohorts that used them.
In the test, there were six questions, each about a different topic. The results of these questions are shown in Figure 8.

Looking at the percentage of correct answers, the fundamentals of engineering score the worst. This also corresponds with what students indicate in the questionnaire.

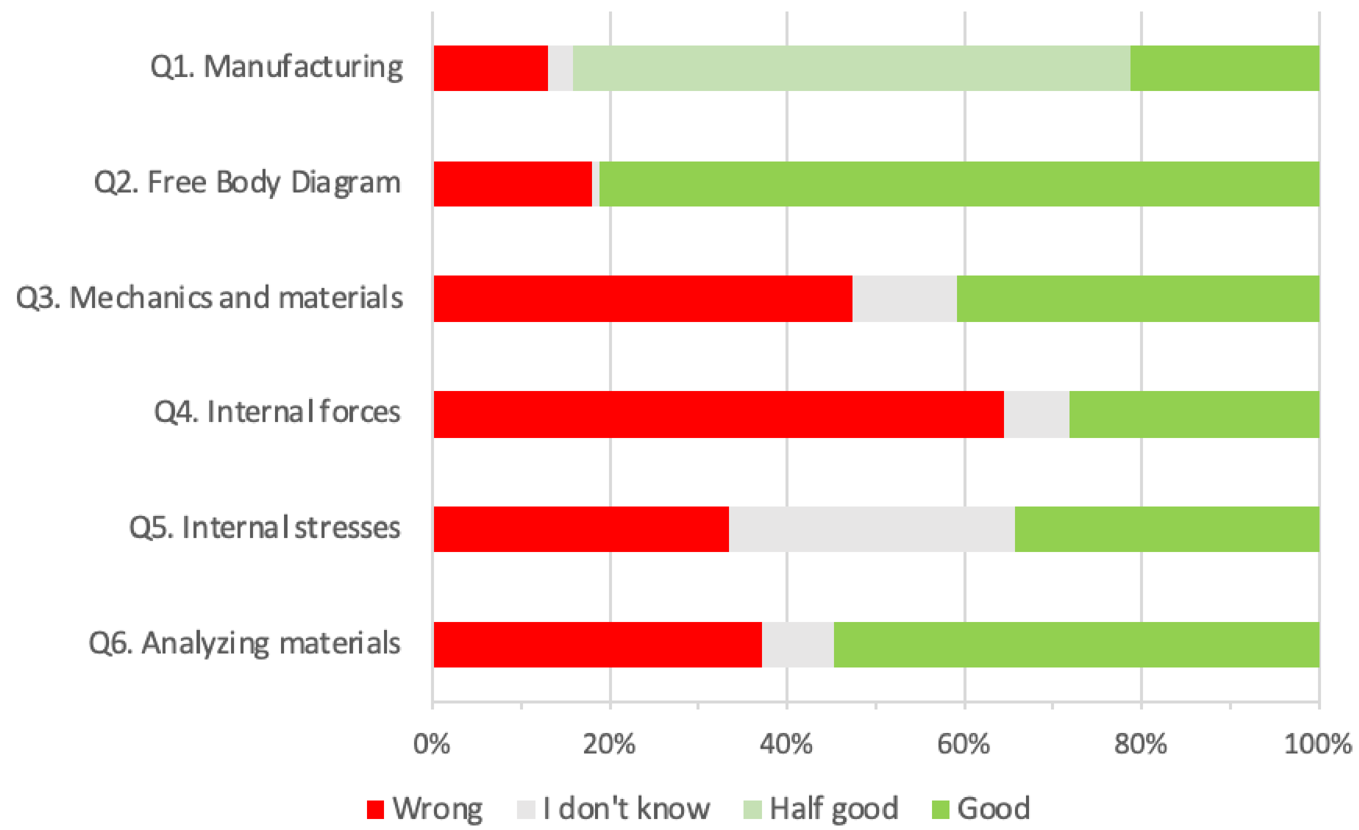


Figure 8: Results per retention test question, total of all cohorts (Persaud & Flipsen, 2024)

2.5 Productive Failure

The used Productive Failure approach is about letting students solve problems that they do not have the skills for without instruction: although it may seem counterproductive to leave them to struggle with something they will definitely fail at, it is actually a "productive exercise in failure" (Kapur, 2008). After this struggle phase, instruction is given. This hopefully creates an "aha!" moment where the solution suddenly seems clear. The students then revisit the problem or they solve a similar one, now with better results. This is distinctively different from the traditional "direct instruction" approach, where a student is taught quite in depth about a subject and then given exercise material (Figure 9).

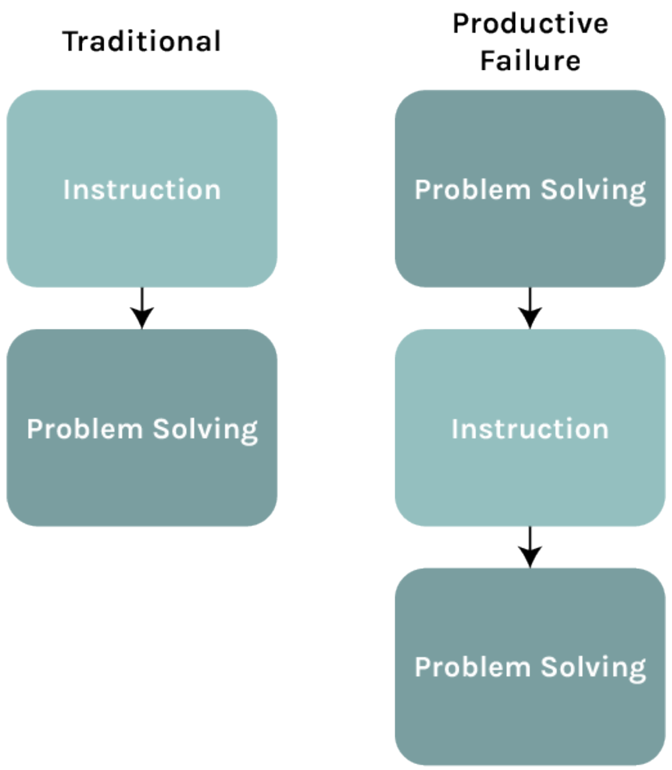


Figure 9: Basic comparison between traditional approach versus PF

In another paper, Sinha and Kapur (2021) prove that the approach works especially for conceptual knowledge and transfer. For industrial design engineers, this specifically is the most relevant type of knowledge. They have to be able to account for mechanical principles when designing, but do not have to go in-depth like mechanical engineers. In this graduation project, it is therefore most relevant that conceptual knowledge about the fundamental subjects of UPE is transferred better.

To achieve this, the Productive Failure Design Cycle (PFDC) is used to create an accompanying workshop assignment. The PFDC is created by Persaud and Flipsen (2023), who apply the PF approach in UPE and other courses in the IDE bachelor curriculum. The cycle is shown in Figure 10.

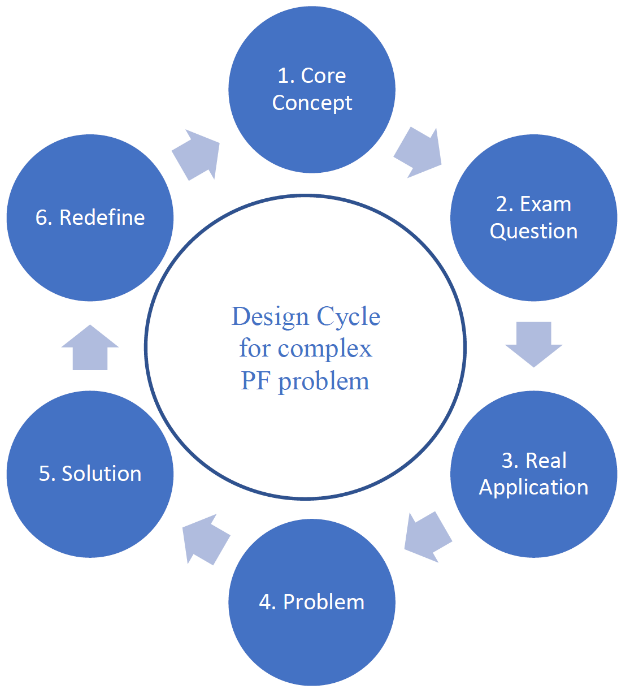


Figure 10: The Productive Failure Design Cycle to come to PF based workshop assignment (Persaud & Flipsen, 2023)

For this project, the LO's of UPE (chapter 2.2) are used for step 1 *Core Concept*. The structure of a workshop is recommended to be as shown in Figure 11. This is how current UPE workshops are organised, therefore this structure can act as a template for the educational module of this graduation project.

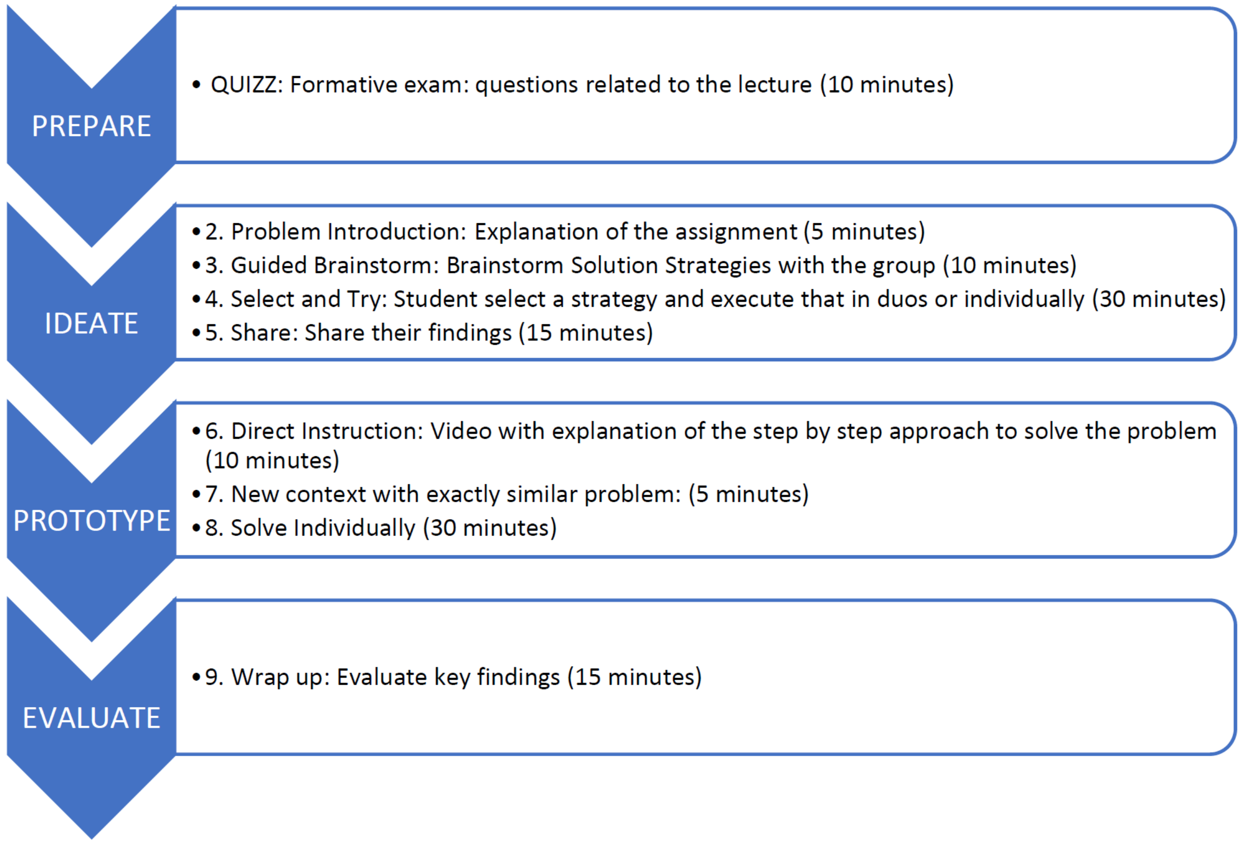


Figure 11: PFDC workshop structure (Persaud & Flipsen, 2023)

2.6 Experiential learning

Using PF, *experiential learning* is promoted in UPE as an autonomous learning approach (Persaud & Flipsen, 2023). The Kolb Experiential Learning Theory is a framework developed by David A. Kolb (Institute for Experiential Learning, 2023). The theory describes how people can learn through experiencing. The ideal process of learning is described in the Experiential Learning Cycle, shown in Figure 12.

Figure 12: Experiential Learning Cycle (Institute for Experiential Learning, 2023)

The four steps of the cycle are integrated in the UPE workshops. They can be recognised in the PFDC workshop structure, where for example reflecting happens through sharing findings in class and in the wrap up phase. These elements should be incorporated in the design of the concept and educational module.

2.7 Learnings from observing usage of the LETT

The Low-End Tensile Tester, originally created by Welling (2014), had the aim to facilitate easier access to tensile testing machines for students. Before its creation, students often only could watch a professional use an expensive, industrial grade machine. This causes students to forget about material testing and material properties after a couple of years. Actual interaction with these principles is way more valuable.
The LETT is a good example of an experiential machine, as it makes a subject normally only taught in theory tangible and concrete. Even though it cannot be used as a professional tensile tester, it still teaches the basic principles and makes it possible to learn about basic material properties like Young's modulus and yield strength, which can be derived from measurements.

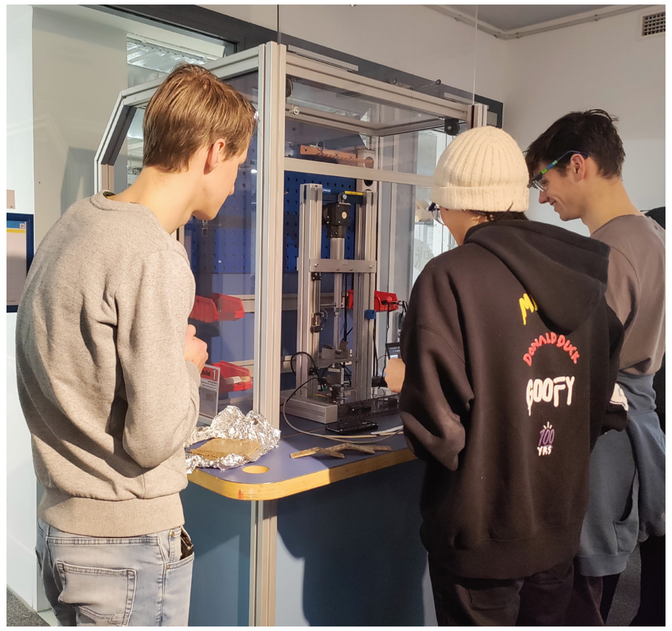


Figure 13: Students using the LETT

The LETT was used during the elective Materials & Manufacturing while running this graduation project. This made it possible to observe how the interaction with this device progresses (Figure 13), possibly leading to insights for the in this project designed machine. The observation is direct and non-participant, meaning the researcher is present in the situation to observe without actively partaking in the activities performed by the subjects (Ciesielska, Boström, & Öhlander, 2017).

A few things stood out:

- Students understand the graphical user interface of the software quite well
- The general idea of the machine is clear and easy to grasp
- It is hard to clamp material samples in the grips
- The material often slips out of the grip
- The material often breaks where it is fixed, leading to inaccurate measurements
- Some students do not have a lot of experience with tools, making the material change a little harder
- The setup can only be accessed from the front, making it harder to work on it with more than one person
- Sometimes students struggle with experimenting, but when they discover something it leads to a positive reaction

The LETT can be used for tension and compression tests and currently also has an add-on for small three point bending tests. It is also possible to test material fatigue with a load cycle mode in the software. The tests can be related to situations that are also common in statics exercises, but one situation that often occurs is not covered. This is the cantilever beam: a beam that is fully supported (fixed) on one end and free on the other.
In the interaction, it is noticeable that some students have more difficulty using the LETT than others. An assumption for a reason that could cause this is a lack of confidence in experimenting combined with a lack of experience with using tools and machines. Students are often used to having to do something because they will get a reward or punishment for it. This can easily make them insecure and refrain from doing something. This is extrinsic motivation, while intrinsic motivation is about doing something because you find it interesting yourself. A theory behind the motivation to do something is the Self Determination Theory (SDT) by Ryan and Deci (2000). The next section will delve deeper into this theory.

2.9 Self Determination Theory

The SDT distinguishes between different motivation types based on the different reasons that make someone take action. Here, the most basic distinction is between extrinsic and intrinsic motivation. Using "the motivation continuum" by Visser (2017), more insight is gained in how these motivation types emerge and how they influence behaviour and emotions (see Figure 14).

Within this project, it is crucial that students engage with the design because they perceive it as both useful and interesting. When students are motivated by genuine interest, their learning experience tends to be more positive and can lead to deeper understanding.

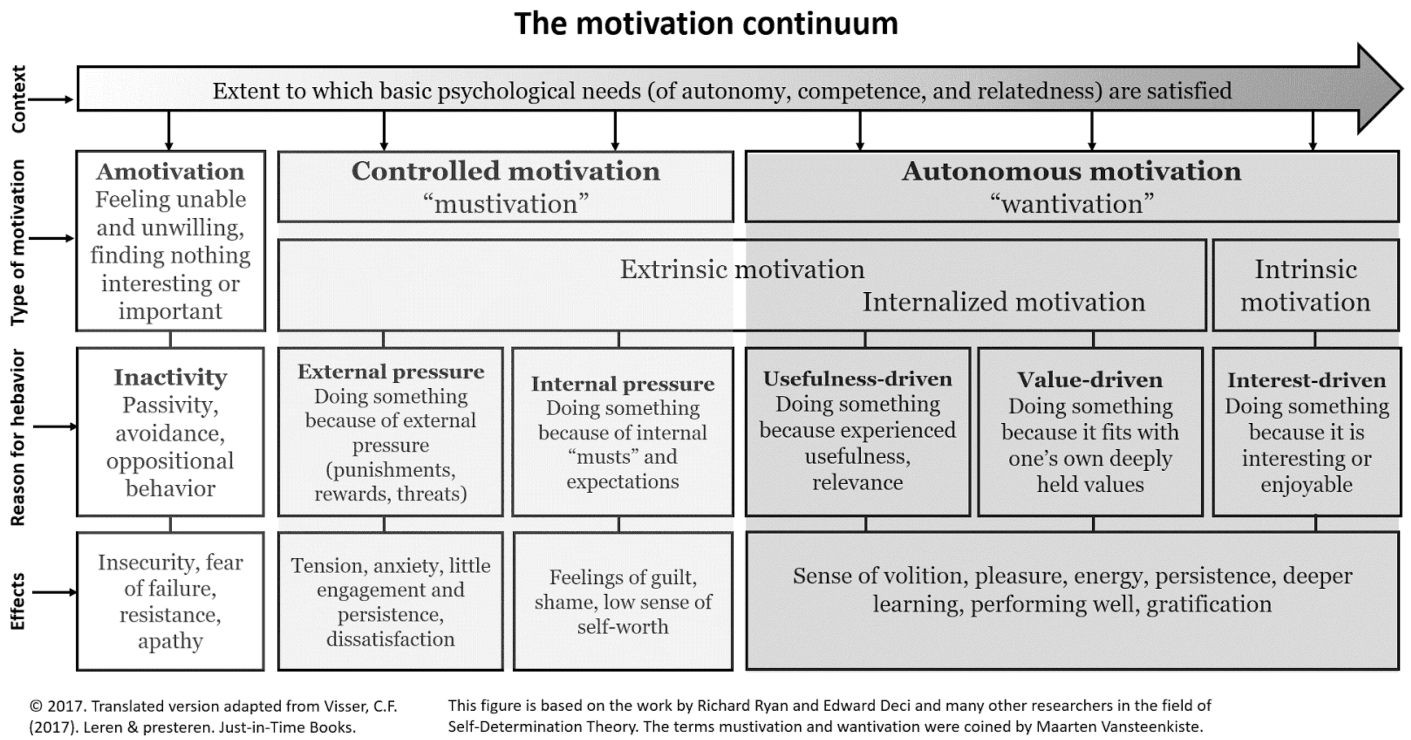


Figure 14: The motivation continuum (Visser, 2017)

In the educational context of this project, specifically during the workshop, students will experience a degree of extrinsic motivation, or what might be termed "mustivation" (Figure 14). They will be assigned to groups and given an assignment. However, it is essential to create a sense of "wantivation," where students feel that the activity benefits their own learning and interests, rather than what the majority is used to: just completing it to earn a grade.

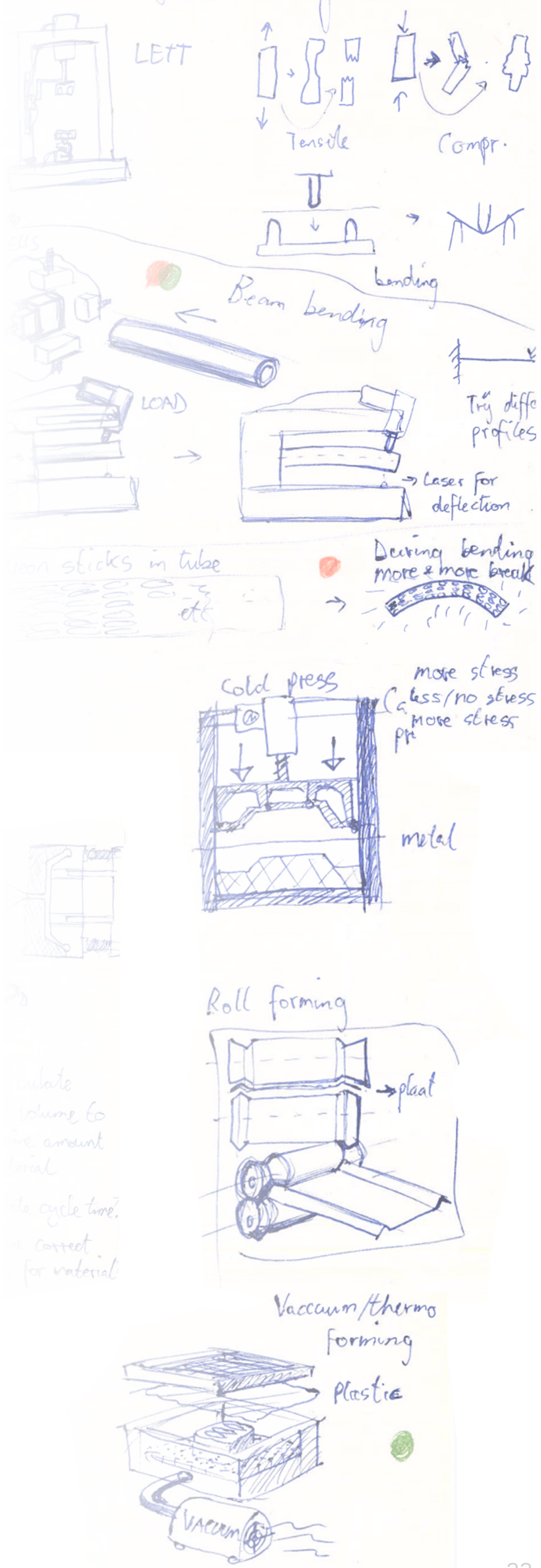
This approach aligns with the Productive Failure methodology, where students tackle problems without direct instructions. This method encourages students to make mistakes as part of the learning process. To effectively engage them, students should believe that the problem is solvable and relevant to their interests. Despite the inevitable mistakes, they will be "doing it wrong for the right reasons," ultimately leading to meaningful learning. This principle should be a key consideration when designing the experiential machine.

3

Initial ideation

To start somewhere, in a few weeks a number of prototypes for different UPE subjects are created. The objective is to come to insightful findings by playing around with possibilities. The goal with these ideas are not fully worked out devices and setups, but to see which ideas have potential. In Appendix 4 they are shown, in this section the most important findings are presented.

Ideas were prototyped for manufacturing and for the fundamentals. The manufacturing processes, like mimicking injection moulding with candle wax, are interesting setups and allow for a lot of experimentation. Other processes could probably be created as well, like sheet pressing, extrusion or blow moulding. Most of these processes are relatively visual and could therefore possibly also be explained by animations, though the idea is that knowledge will stick better when the students get hands-on experience.



A topic that is harder to explain with pictures and animations is statics. There are standard icons for the supports that are used in FBD's, but they often do not resemble the real world. The vector arrows for forces and moments can also be quite abstract. To make it more tangible, the supports were made into physical versions (shown in Figure 15).
They can be swapped around, put in different positions and configurations. This way, students can discover how they really act and maybe find the connection with real life supports and fixtures. Especially when using a flexible material for this beam, it can be observed what effect the different supports have on the bending of the beam.
At the same time, these are quite literal translations, and only give limited insight into statics and FBD's. A more advanced version would be the same set, but with sensors that can register the load and torque in different directions. This way, students could for example check their FBD's in real life, enabling them to play around and experiment.

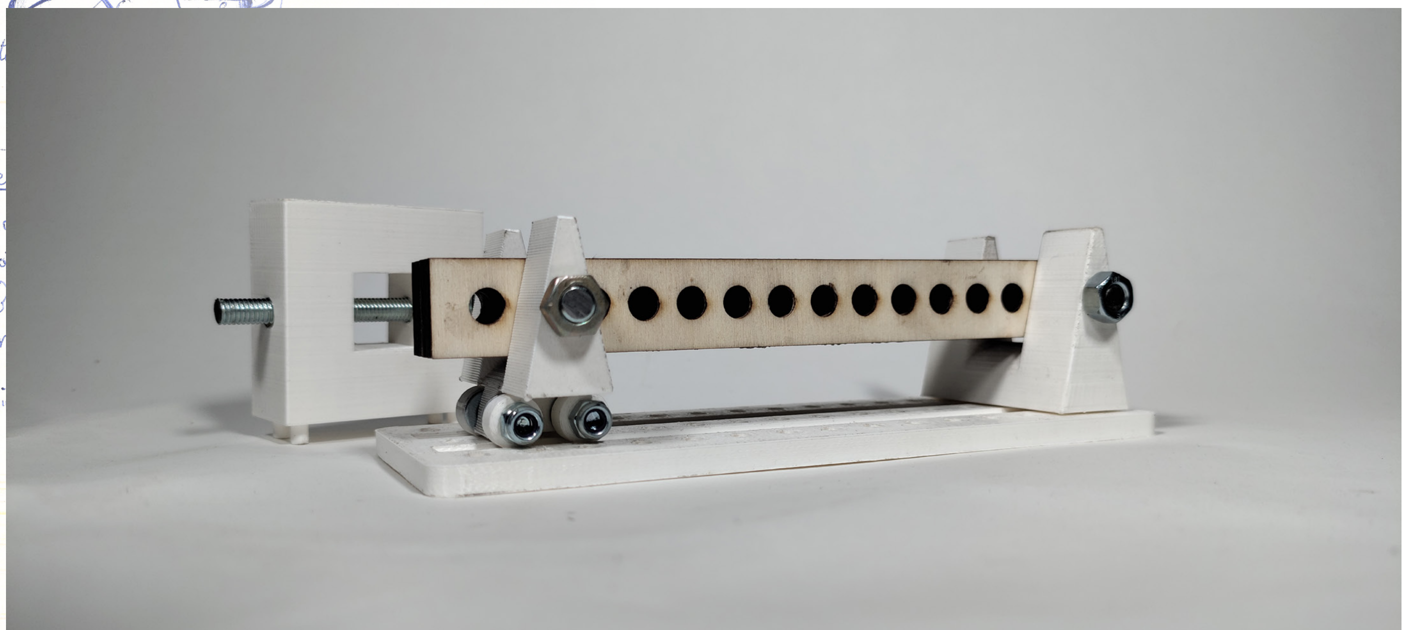
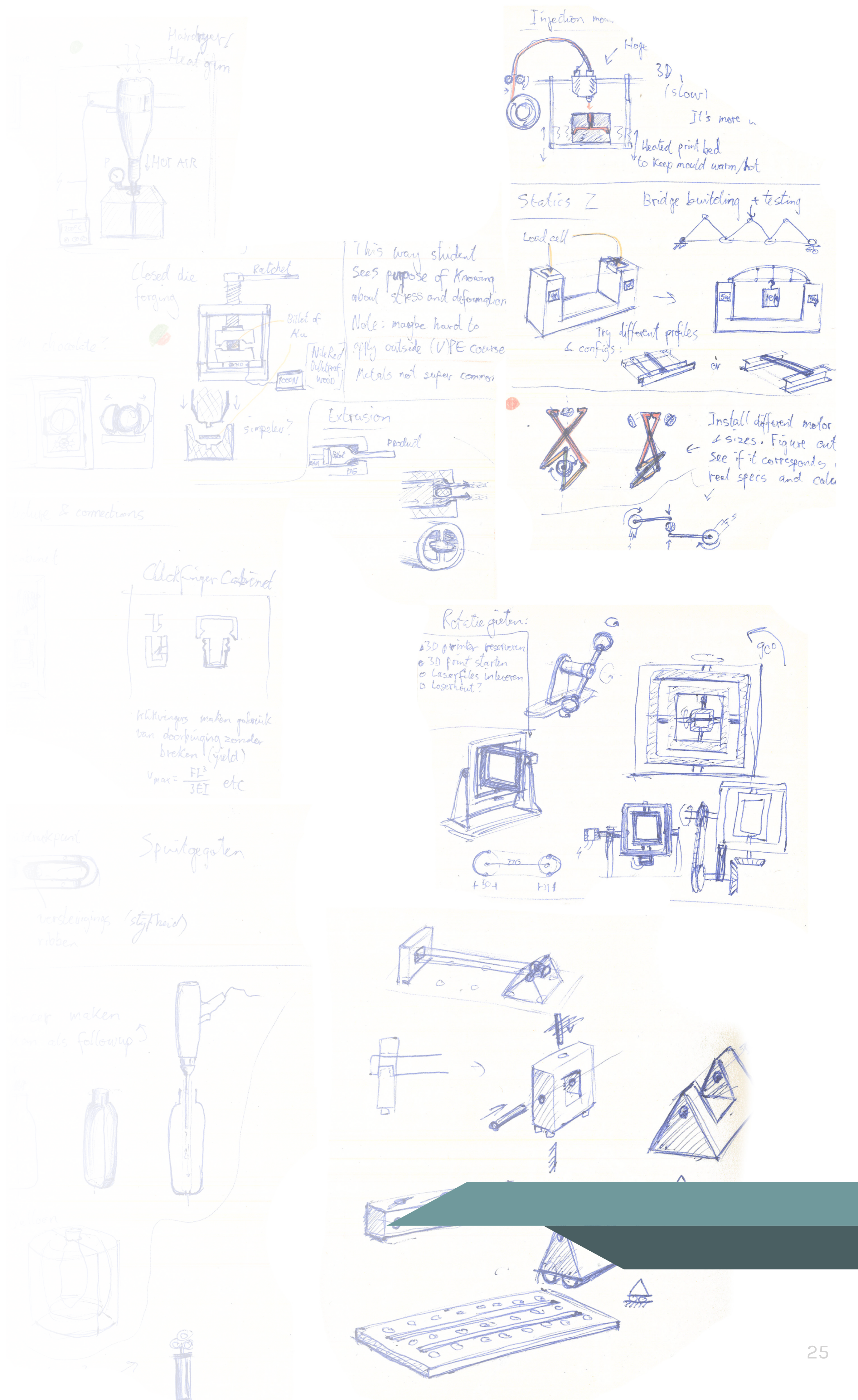


Figure 15: Physical set of typical supports in statics



Exploration findings & design direction

This first phase of exploration leads to the identification of three main factors in this project. This also comes with a choice of direction, as discussed in section 4.3.

4

4.1 Educational context of UPE

First of all, there is the educational context of the UPE course. It comes with the mentioned learning goals, derived from FAL's, and consequently the subjects that are taught. It also sets boundaries, like the fact students have one afternoon for a workshop and one week per subject. The methodology is also part of this, which is the Productive Failure approach. During a workshop, students work in groups. This is an element that needs to be taken into account in the design.

4.2 Student related considerations

Then there are the students themselves; they struggle with certain subjects and concepts. They amongst others, indicate the fundamentals of engineering to be the hardest (statics, NVM lines (internal forces) and stress & strain). They also do not score well on these in the retention test by Persaud & Flipsen (2024), as mechanics of materials (which covers stress & strain) and internal forces and stresses have the lowest percentage of correct answers. A question in which students have to choose the correct FBD out of 9 options is answered well, but statics is about more than picking the right FBD. Creating your own FBD requires a higher Bloom's level, specifically *Applying*, than simply choosing the correct one, requiring *Understanding*.

Beyond the challenging material, students also face a shift in educational approach. As mentioned earlier, they are accustomed to a reward/punishment system from high school, which is rooted in extrinsic motivation. This can limit their willingness to experiment and fail, and overcoming this restraint is a challenge. Since UPE is one of the first courses they take, it plays a key role in initiating this change.

4.3 Choice of UPE subject to be addressed

Lastly, there is the subject that students need to get a better grasp of, with the experiential machine as a tool. This needs to be chosen as a direction for the rest of this graduation project. The exploration and ideation on the different subjects aids this decision. The subjects that already have an experiential setup are left out, and for the others the following arguments apply.

Statics is chosen as the direction for this project, as it offers a chance to create something new that can help students overcome one of the larger pitfalls. To come to a fitting design, a deeper dive into this subjects needs to be taken, after which concepts can be created.

Subject	Reasons (not) to choose
Statics	+ Seems biggest challenge
	+ Big pitfall for students
	+ Improved understanding helps other subjects
NVM lines	— Hard to make physical
	— Derives easier from statics
Manufacturing	+ Offers lots of experimentation for students
	— Processes are already quite visual
	— Other graduate Robin Taen will continue with this subject
Product architecture	— Has low priority in exams and education

4.4 Additional requirements

Based on the previous research, new requirements are added to the initial requirements and some requirements can now be specified. The new requirements are shown in Table 2.

After taking a deeper look at the subject of statics, more requirements will come up and they are all presented in chapter 6.

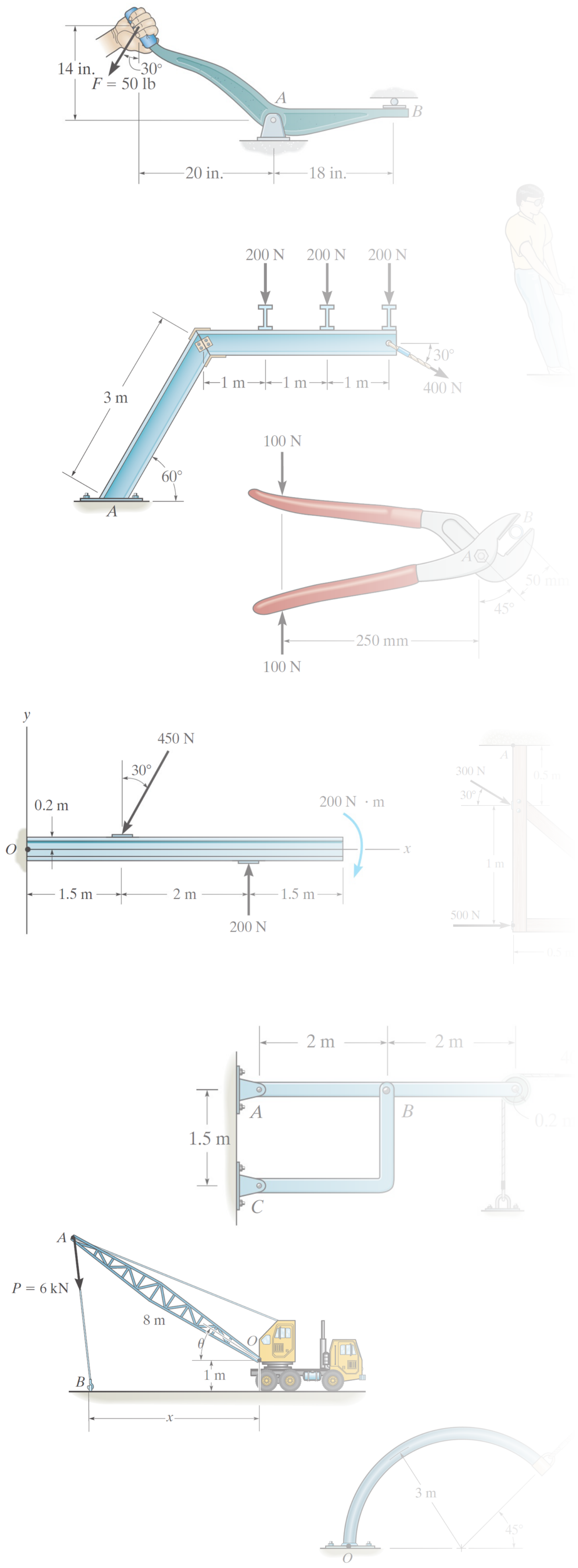
Table 2: New requirements

Requirement
The design and assignment must be structured so that they can be fully used and completed within a 4-hour afternoon workshop
Must improve the retention time of students over a traditional approach
Must offer a physical, hands-on experience → Must offer a physical, hands-on experience in statics
The assignment module needs to follow the structure as suggested in the Productive Failure Design Cycle
The design must require students to manually set up an experiment with the machine (no plug-and-play)
The design must be accessible to at least two persons at the same time
The design must incorporate elements that enhance students' intrinsic motivation ("wantivation") by ensuring that they perceive the activity as enjoyable and interesting

Current challenges in teaching statics

With this direction in mind, the topic of statics can be explored further. Mostly, the relevance of the different topics that fall under statics and the connection to reality are evaluated.

5



5.1 Abstract nature of statics exercises in mechanics

Students are traditionally taught statics through exercises from books like *Engineering Mechanics: Statics* (Hibbeler, 2016). This book specifically is used in the UPE course as well. The 'theme' of the exercises that appear in this book can roughly be divided into two:

1. Exercises about calculating if something is balanced or about leverage (transmission of forces)
2. Exercises about calculating input for determination of stress and strain

The first type of exercises often contain realistic situations like tools, cranes or car parts. They have familiar graphics and are easy to imagine (see Figure 16).

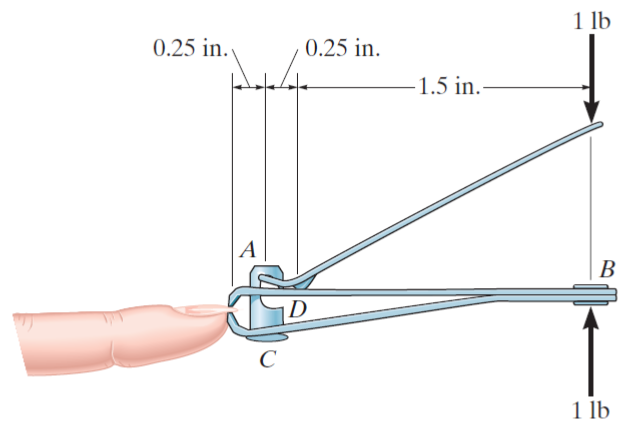


Figure 16: Prob. 6-95. From *Engineering Mechanics: Statics* (p.331), by Hibbeler, 2016.

The second category is relatively abstract, as the examples are often not something that is easy to imagine. Frequently, the object in the exercise is a shape or construction that does not occur in or is disconnected rom real life like in Figure 17, or they are extremely specific exercises. Imagining these things can be quite hard.

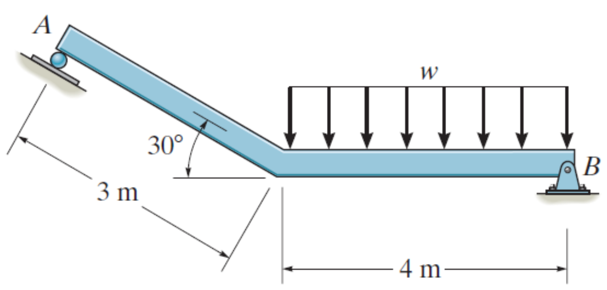


Figure 17: Prob. 5-22/23. From *Engineering Mechanics: Statics* (p.236), by Hibbeler, 2016.

5.1.1 Sampling exercises experiment

The ratio between these abstract exercises (stress and strain related) and more concrete ones (about balance and leverage) is evaluated. This way, the result can lead to a conclusion of what is more important to learn for students. In this small study, 280 exercises from the book *Engineering Mechanics: Statics* (Hibbeler, 2016) were sampled and categorised. This was done with chapters relevant to the UPE courses: chapter 3.3, 4.4-4.7, 5.4, 5.7 and 6.6. For some chapters, exercises were skipped that involved three-dimensional force systems and trusses as they are not covered in UPE. Simultaneously, an entire chapter about friction was skipped, as it is neither covered.

The result shows that 31.8% of exercises is in category 1, and 68.2% in category 2. The full counts per chapter are in Appendix 6. Clearly, over two thirds of the exercises are of the abstract type and relate more to stress and strain. If the exercises about trusses would have been taken into account, this number would be larger even.
What also stands out, is that the subjects of the exercises are clearly related to mechanical engineering. This makes sense, as the book was assumably originally made for these students. At IDE, students used to follow statics at the mechanical engineering faculty, but that has changed. Now, the theory in this book is relatively less relevant as typical industrial design products involve statics in different ways. For example, office or aeroplane furniture is more relevant in this field of engineering, while still containing statics-related elements.

5.1.2 Findings from sampling experiment

Concluding, in engineering the focus is more on finding reaction forces and determining if products or constructions will hold up to certain loads, or that they might fail. Therefore, considering statics in this project, it is more relevant to design something related to this.
It is also clear that the abstraction of these exercises can be a struggle for students. This also relates to the SDT again, as without a clear usage of theory, there is less "wantivation". Teaching the application of the discussed type of statics in an improved way theory could increase the understanding of the need for it.

The application of the statics situations that are input for stress and strain calculations can be found in bending of beams. Often, a situation can be reduced to a beam, of which the amount of deflection can be calculated. When the situation only involves tension or compression, the situation is one-dimensional. The LETT revolves around those situations. To take a step further, beam bending could be considered as an interesting topic for the design.

5.2 Understanding beam deflection

The cantilever beam in one of the simplest configurations is shown in Figure 18a. It is fixed on one end and has a point load on the other. The fixed support means that there is two reaction forces and one reaction moment (Figure 18b). This moment is not something that is visible in real life, and makes it therefore an abstract phenomenon that can be hard to imagine.
When continuing from statics to assessing deformation, the beam would deform like in Figure 18c. Using $\delta = \frac{FL^3}{3EI}$ and $\theta = \frac{FL^2}{2EI}$, the maximum deflection and deflection angle can be found. These common deflection formulas (in Dutch called "vergeet-me-nietjes") are valid under certain conditions, but function well as approximations.

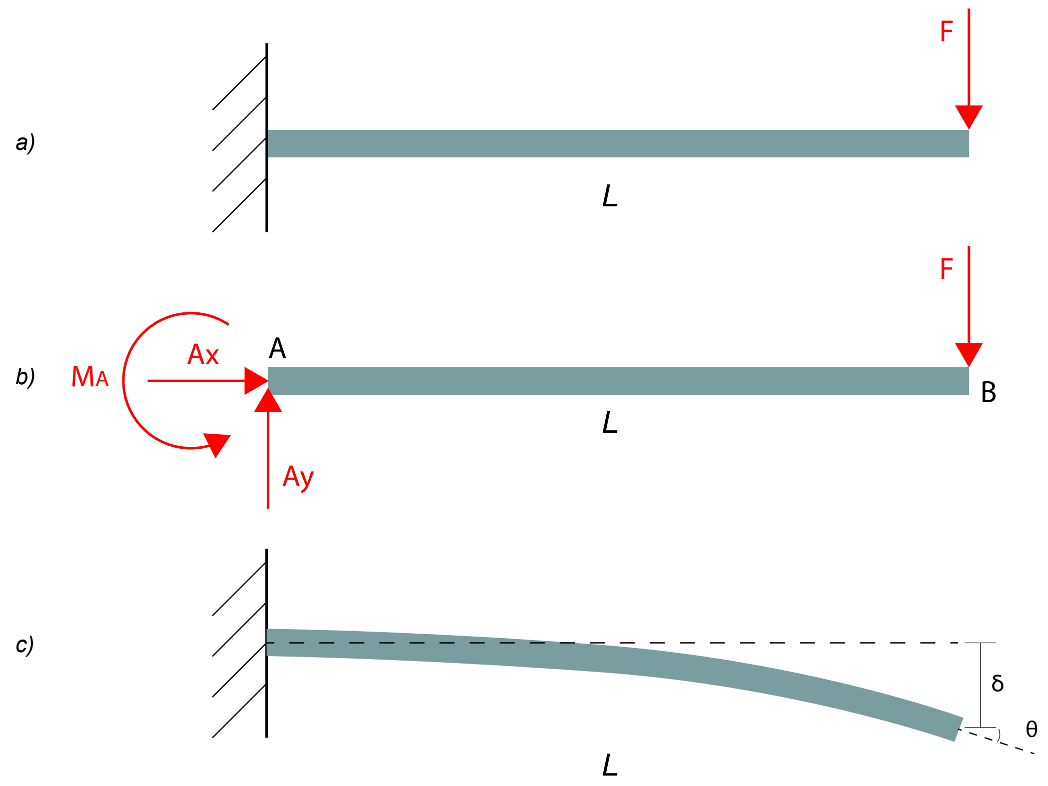


Figure 18: The cantilever beam

If the load is not a point load but a distributed one, the deflection formula is $\delta = \frac{qL^4}{8EI}$, with q being the distributed load (unit N/m). The formula becomes simpler when the load is not caused by a force, but by a moment: $\delta = \frac{ML^2}{2EI}$.
Another effect that can occur when applying a load to a cantilever is the "wagging" of the free end when a load is applied somewhere else on the beam. To calculate the deflection of the free end where the point load applied in the middle of the beam, the formula is $\delta = \frac{5FL^3}{48EI}$.

Real life applications that these cantilevers appear in, are among other things:

- Wall mounted products like bicycle racks, lamps, shelves, TV mounts
- Furniture like chairs with armrests or designer fauteuils
- Constructions with overhang in the built environment
- Flag poles
- Arms for e.g. microphones (boom arms) or dentist/surgery equipment
- Mechanical constructions in automotive or aerospace engineering
- Sailing boat masts
- Street furniture or infrastructure like benches, street lanterns or poles
- Snap joints in product architecture

Another common supported beam configuration is the simply supported beam, shown in Figure 19a. It is worth noting that we are limiting ourselves to statically determinate situations, meaning they are stable and all unknown reactive forces can be determined from the equations of equilibrium alone (sum of X and sum of Y direction forces and sum of moments).

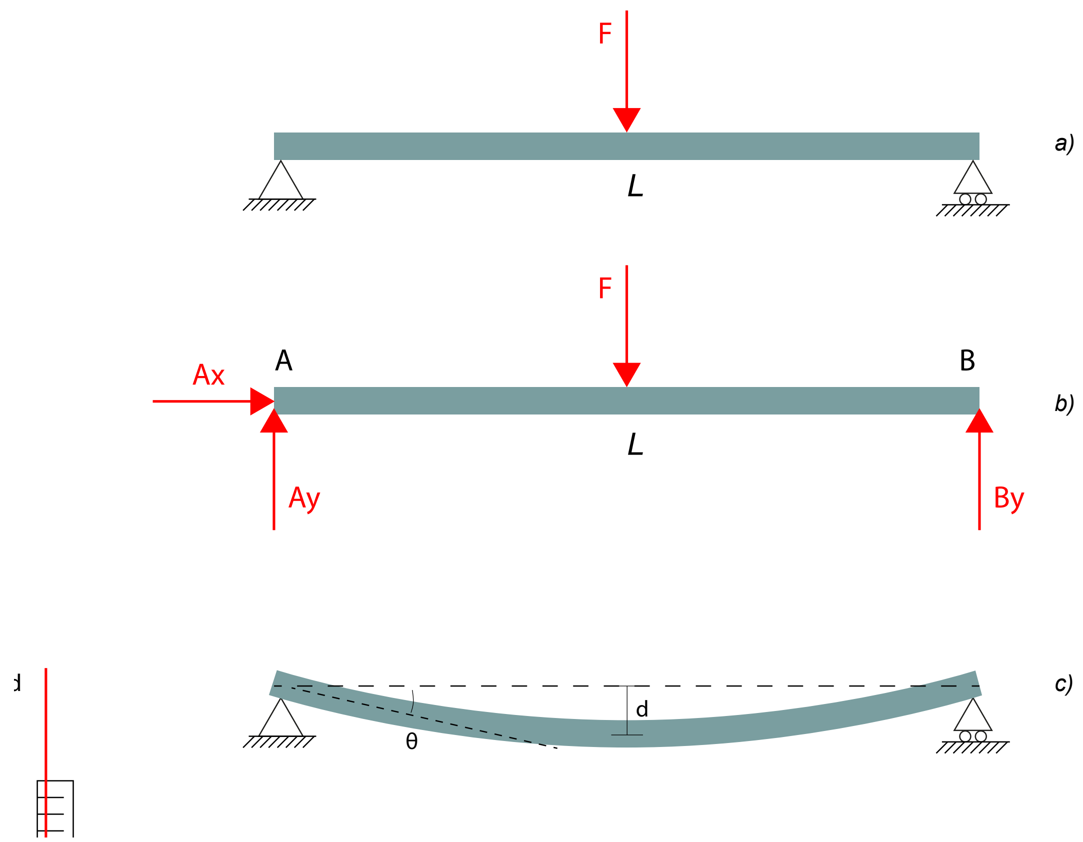
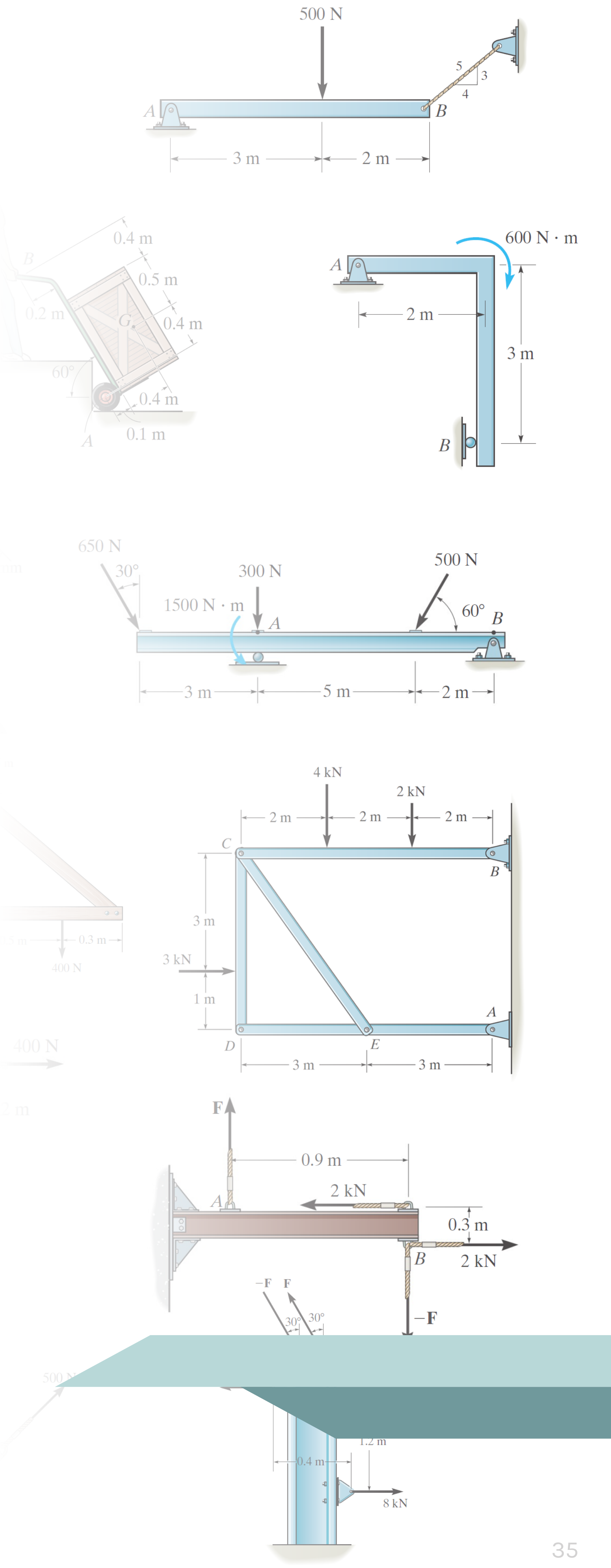


Figure 19: The simply supported beam

Here, there are no reaction moments as shown in Figure 19b. In this specific situation, there are in fact only vertical reaction forces. This corresponds with the three point bending test that can be performed with the LETT. The result would look like Figure 19c. The formulas for this are $\delta = \frac{FL^3}{48EI}$ and $\theta = \frac{FL^2}{16EI}$.
What is interesting to realise, is that these beams could be viewed as springs. This can actually also be derived from the deflection formula, as the force exerted by a spring can be described by Hooke's law, $F = -kx$.
Here F is the spring force (N), k is the spring constant (N/m) and x is the displacement from the spring's equilibrium position (m). In the cantilever beam deflection formula, F is the load applied on the beam, x is the deflection of the beam and k is the equivalent of $\frac{L^3}{3EI}$, as this is constant too.

5.3 Choice of focus within statics education

From this evaluation of statics education follows the insight that to make a relevant concept, statics could be combined with what normally follows after: stress and strain. Specifically, bending of beams is a more visual and in designing relevant phenomenon. Therefore, in the following concept development phase, this is taken into account. The cantilever beam has an extra focus, as it involves the abstract counter moment, is relevant in design, not covered with the LETT and its deflection equation lends itself well for teaching relevant design properties.



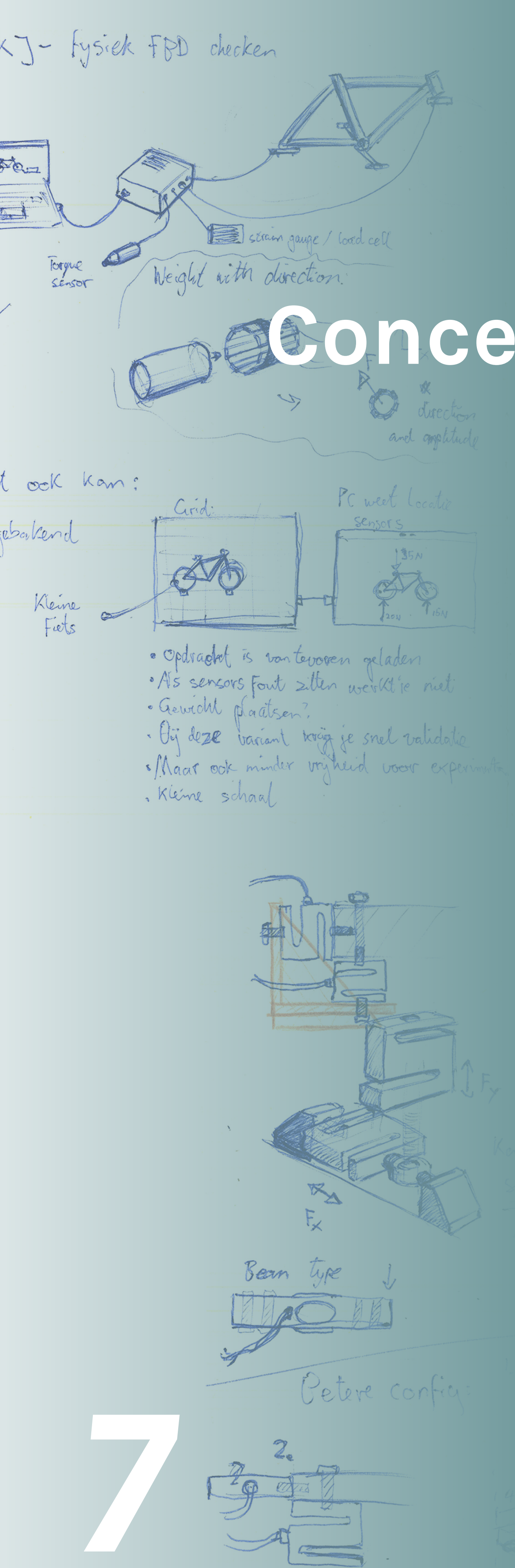
6 Design requirements

The design brief, conducted research and exploration lead to a set of requirements, organised in the Program of Requirements (PoR). The problem definition is now also refined, as it is decided to focus on the combination of beam deflection and statics. The PoR is established with the help of chapter List of requirements in the DDG (Van Boeijen et al., 2017b).

Now, the main question is ***Which experiential machine can serve as an educational tool to teach statics in a hands-on way with a focus on beam deflection?*** The answer, or the final concept, will have to meet the requirements listed in Table 3. During the design process, new requirements can come up. These are listed in the corresponding chapter. The full PoR can be found in Appendix 7. To keep track of the status of each requirement, the '*Ampel* method' (German for traffic light) as used by car manufacturer Audi is used, inspired by G. Nijenhuis (personal communication, September 6, 2024). With this method, the status of each requirement is either not achieved (red), in process (orange) or achieved (green).

Table 3: PoR

Nr	Requirement	Derived from
R1	The design and assignment module must enable the Productive Failure approach	Educational context
R2	Must offer a physical, hands-on experience in statics and beam bending	Educational context + Research (4.3 + 5.3)
R3	Must be scalable to 20 units	Educational context
R4	Cost must stay under €500	Design brief
R5	The design and assignment must be structured so that they can be fully used and completed within a 4-hour afternoon workshop	Educational context
R6	Must improve the retention time of students over a traditional approach	Retention (2.4)
R7	The assignment module needs to follow the structure as suggested in the Productive Failure Design Cycle	Productive Failure (2.5)
R8	The design must be accessible to at least two persons at the same time	Observation of LETT usage (2.6)
R9	The design must require students to manually set up an experiment with the machine (no plug-and-play)	Productive Failure (2.5)
R10	The design must incorporate elements that enhance students' intrinsic motivation ("wantivation") by ensuring that they perceive the activity as enjoyable and interesting	SDT (2.7)



Concept development

7

In this chapter, the concept development process is presented. As a clear direction has been chosen, different concepts with the same purpose can be created. The most important ones are first presented, after which a reasoned choice is made. This concept is developed further in detail afterwards.

7.1 Scenario for concept generation

To illustrate the role the concept needs to play, a simple storyboard is created in which the to-be-designed concept is treated as a 'black box.' This means that while it has no embodiment yet, the desired interaction and effect on the user are depicted. This approach is loosely based on the Storyboard method from the Delft Design Guide (Van Boeijen et al., 2017e), with the added 'black box' serving as a means to keep both the designer and client unbiased toward the final embodiment while still enabling communication of interactions and purpose. The storyboard is shown in Figure 20.

This storyboard forms a starting point for ideation on concepts. In this scenario, the Productive Failure approach is implemented as the student tries to solve the problem before getting direct instruction. The Self Determination Theory is implemented by providing a fascinating, intriguing device, as this should spark interest to create intrinsic motivation. The black box is deliberately made mysterious. The device must be stimulating so that the student wants to discover it themselves. The imagined assignment that comes with the workshop in the storyboard is derived from a real application of statics and bending, to teach the student the relevance of the theory and principles. The sense of relevance also helps with "wantivation".

Figure 20: "Black box" storyboard to show imagined interaction (includes imagery created with ChatGPT (OpenAI, 2024))

7.2 Process

In this phase, multiple concepts are created. The process of coming to the most promising concepts is shown in Figure 21. Some ideation sketches that precede this can be found in Appendix 8.

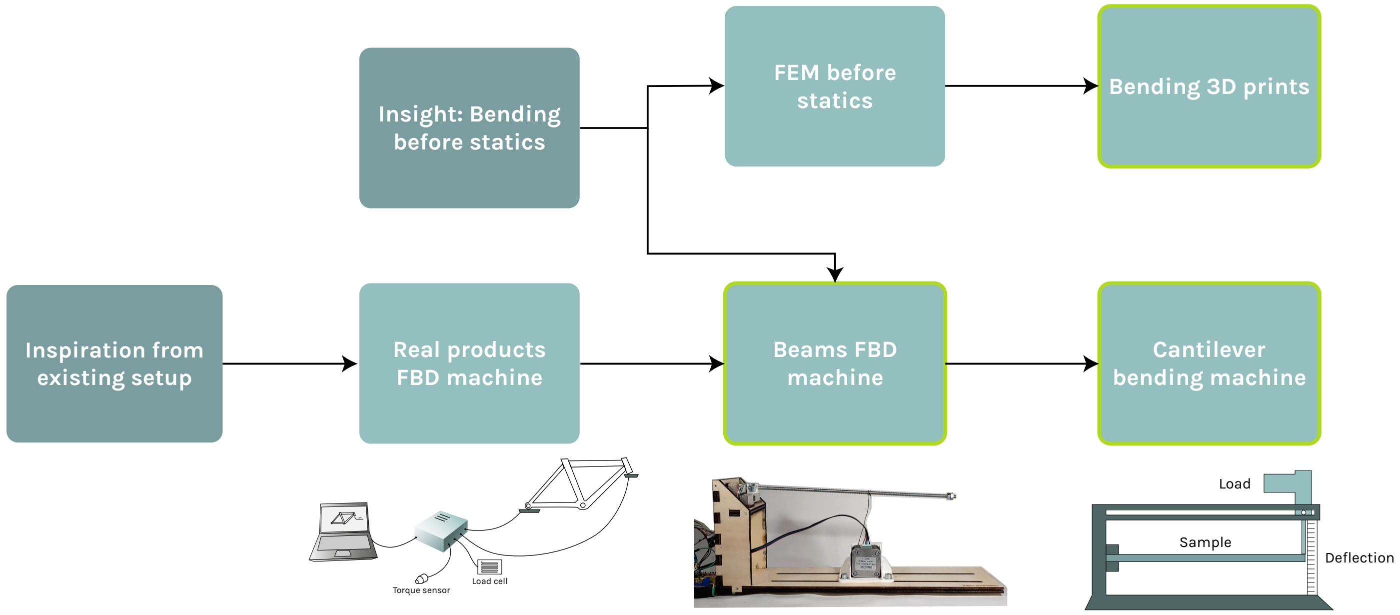


Figure 21: Process of concept generation

What inspired part of this phase is the way the teachers currently offer some way of doing real life FBD checks. They for example give students small scales on which they put a ruler and some type of load that the student can move along the beam, or a small stepladder with one side on a scale. This way, students can see it is possible to simplify real life situations to a better comprehensible interpretation, like the simply supported beam.
The ideation, combined with earlier ideation from chapter 3, leads to three of the most promising concepts (green border in Figure 21). In Appendix 9 two other iterations of the following concepts are shown.

7.3 Concept 1: Bending 3D printed beam-like objects

This concept is a physical addition to another concept, called "FEM before statics concept", presented in Appendix 9. The Finite Element Method (FEM) is a numerical technique used to solve complex engineering and mathematical problems. In that concept, students first get to perform a static study in CAD software without instruction. This is followed by detailed explanation, particularly about support types and load placement, like used in statics. This concept does however not meet the basic requirement of a physical experience at all.
An idea to expand this with a physical element, is to offer 3D-printed versions of the product that the students have in the CAD software. The students are given tools and ways of applying a load. They are allowed to break the product, but are asked to predict where it will deform the most based on their FEM simulation. If reality corresponds with the simulation, this can give a rewarding feeling. However, it is just as valuable if it does not correspond; the student can now ask themselves why this is the case.
With this addition, the scenario changes as shown in Figure 22.

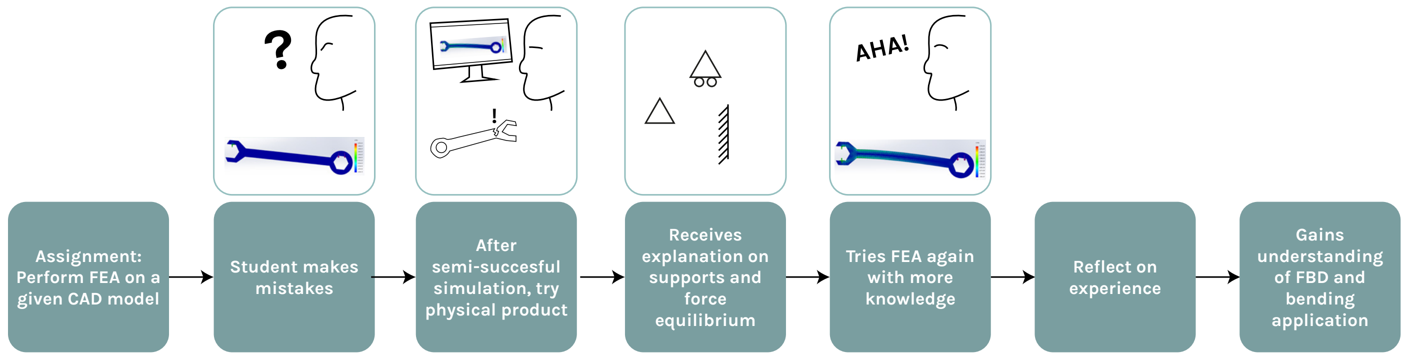


Figure 22: FEM combined with bending 3D beams scenario

Two of these 3D printed models were prototyped, shown in Figure 23. Even though 3D prints behave quite different from e.g. cast chrome-vanadium tools, the location of failure will often be the same due to the similar geometry.

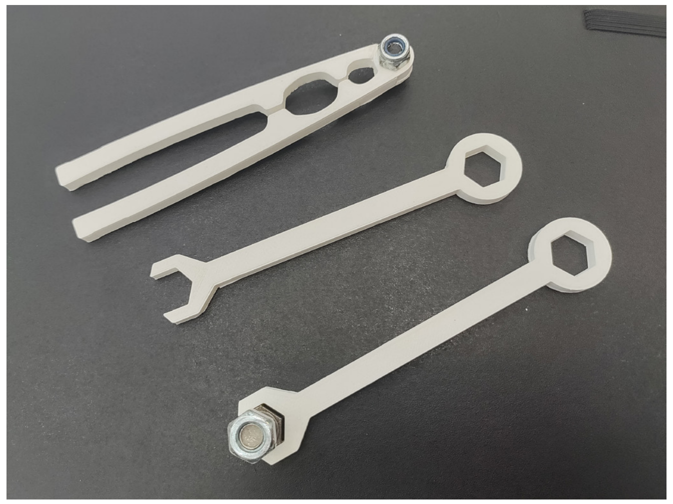


Figure 23: 3D printed, simplified nut cracker and wrench

A comparison between the static study in SolidWorks and the 3D print is shown in Figure 24. This shows that the print failed at approximately the same spot as where the simulation showed the most stress.

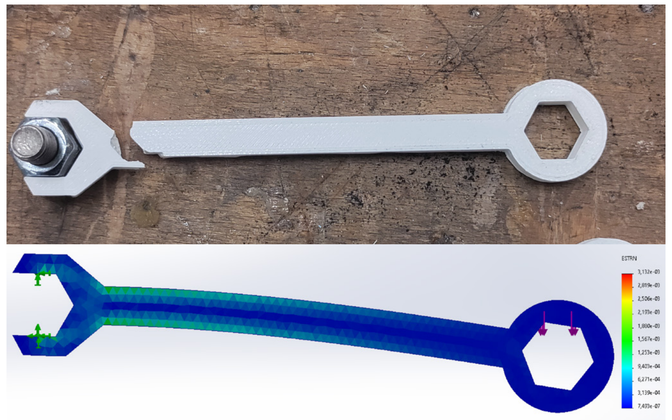


Figure 24: Comparison between FEM simulation and 3D printed version of the same model

7.3.1 Discussion

The mentioned difference in behaviour of 3D prints is a limitation of this concept. The way the products fail, is dependent on the way it was printed. If the lines in the print run perpendicular to the length of the model, this creates a weaker connection than if they run in the longitudinal direction. It could therefore be debated if working with 3D prints creates a sufficiently realistic experience.
Besides this, the 3D prints are broken in this concept. That means they are only used one time, which is not ideal from a sustainability perspective. Even though this is not one of the requirements, responsibility for the effects on the environment has to be taken as well. The effect can be minimised by recycling the broken prints properly, which is fortunately not difficult as there is a dedicated PLA recycling bin in the faculty's workshop. Printing still requires electricity, and the recycling process is also energy demanding. Recycling PLA takes around 32.1 kWh per kg (Kumar et al., 2022).

7.4 Concept 2: FBD machine - beams

This concept is also an iteration on another concept, called "FBD machine - real products" (Appendix 9). Its idea is to use load cells with real products like a bicycle frame, to enable students to check their FBD's in real life. This bridges the statics theory with reality. It however does not relate to bending of beams as much.
In this concept, it is tried to use the same beam type load cells in a more controlled setup. In this case, a cantilever beam setup is taken as a base and with a stepper motor a load can be applied anywhere on the beam. The load can also be applied at an angle, causing a reaction force in the X direction. This way, simple FBD's could be recreated. On the fixed end, there are two load cells that measure in two directions, like the X and Y reaction forces in a fixed support in an FBD. This is shown in Figure 25.
This is the cantilever situation, which as mentioned in chapter 5 means there is also a reaction moment. The moment is not measured, but that would be an improvement. The same device could also be used to mimic the simply supported beam from chapter 5, which would include an extra load cell on the other end and different connections. In that case, there is no reaction moment, just three reaction forces (Figure 19b).

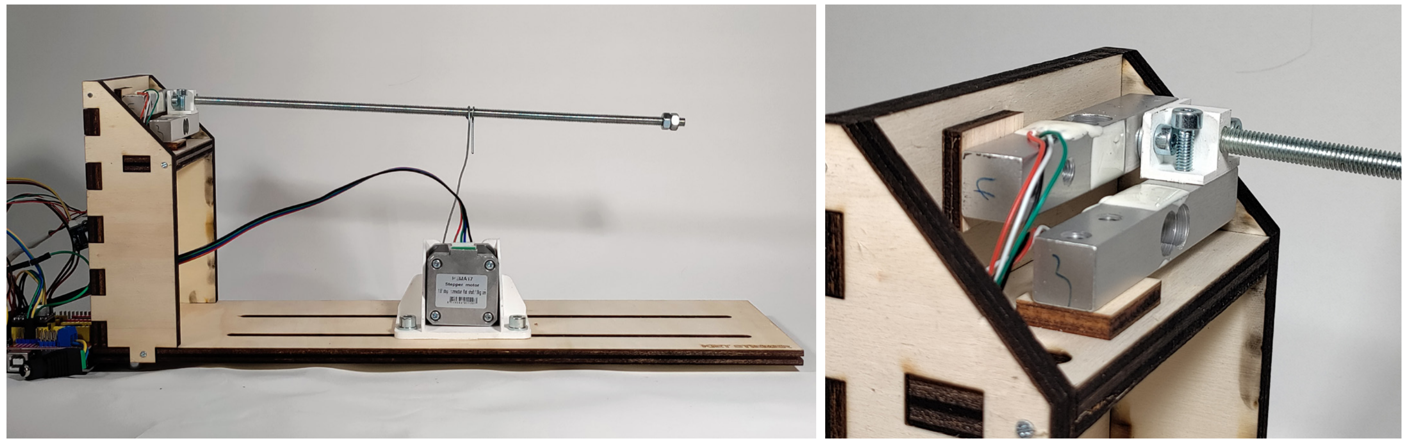


Figure 25: Cantilever with load application and reaction force sensors

7.4.1 Discussion

It quickly becomes evident that this setup is challenging due to that particular moment generated at the fixed support. As a force is applied on a fixed bar, the bar wants to rotate and pulls on the X direction load cell, making the measurements complex and not corresponding with theory. This realisation highlights the necessity of something to counter the moment that is generated, possibly being a "moment", or torque, sensor. Just adding a torque sensor to two load cells is unfortunately hard to realise. Consequently, this concept proves to be quite complex. It clearly shows how statics theory is always an idealised situation.

7.5 Concept 3: Cantilever bending tester

The FBD machine concept leads to the realisation it is also suitable to measure beam deflection with it. Statics are primarily taught to enable subsequent calculations related to deformation and failure, as concluded in chapter 5.1. Therefore, an inverted approach can be considered: focusing initially on bending beams, followed by the theory of statics. This approach might allow students to better understand the practical significance of the theory, creating a 'need to know', which based on the Motivation Continuum (Visser, 2017) could increase students' motivation. This is similar to the FEM before statics concept, but is a way more physical implementation. To do so it is not necessary per se to have load cells and a moment sensor for the reaction forces, the concept could also be just about calculating and measuring deflection of beams under load. In Figure 26, a concept illustration is shown.

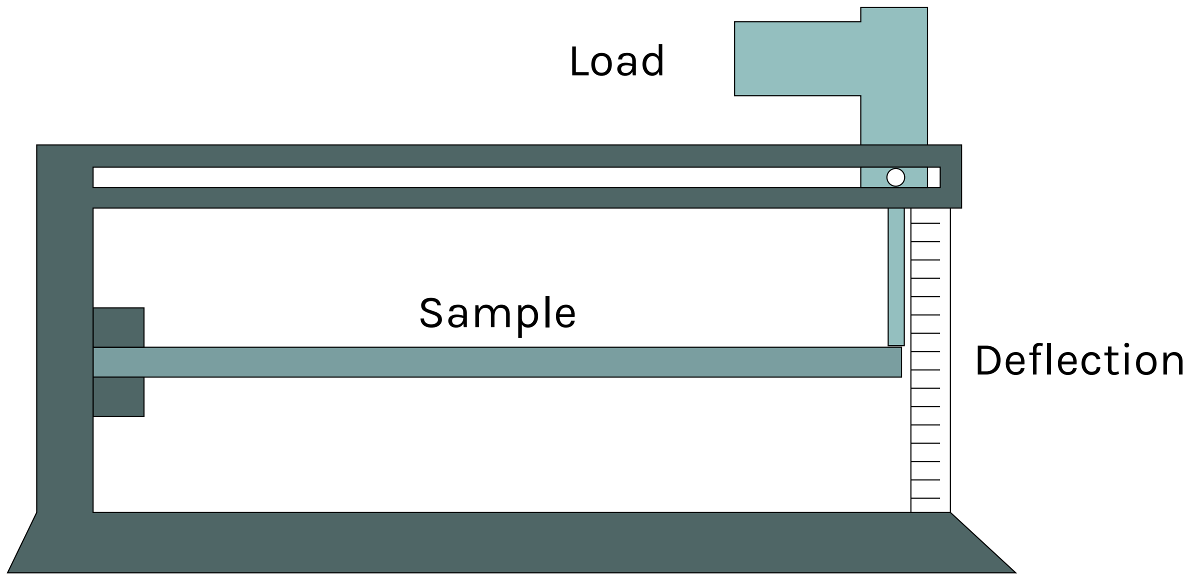


Figure 26: Cantilever bending tester

The embodiment of the concept has to be determined, but this illustration shows the basic setup. A sample of a certain material and shape is fixed in the device and a load can be applied anywhere on its length. The load could potentially also be applied at an angle, or with some extra additions a distributed load could be applied. With a device like a ruler, the deflection can be measured. This can for example be compared to theoretical values. These calculations can be done with the common deflection formulas as mentioned in chapter 5.2. From the formula's elements students can be taught a lot about loads, moments, material types and geometry. These are all relevant design elements as well. Furthermore, this approach could follow the Productive Failure principle as students are encouraged to play with the bending of different type of beams, make mistakes, and consequently learn about the theory behind it.

7.5.1 Discussion

It is not feasible to test the inverted approach of teaching mechanics topics before statics within this project, as this first requires a working prototype. This has initial priority and considering the time span of the graduation project, it is possible to create a machine that allows students to engage with this topic, but a larger scale test could be performed in the future. This test could evaluate the effect of this approach on the understanding of statics compared to a traditional way of teaching.
This concept focuses purely on the bending of beams, and the connection to statics needs to be made separately in instruction or by giving some direction for discovery by the student. At the same time, it would be interesting for students to get a better understanding of the reaction moment in the support. For this concept, it is recommended to look into ways of doing so.

7.6 Concept choice

From the presented concepts, one is chosen based on the potential, relevance and how well the concept fits the requirements. The decision is supported with the *Weighted Objectives method* from the Delft Design Guide (Van Boeijen et al., 2017f).

Five main criteria are identified and each is assigned a weight, together they add up to 100. The criteria are presented in Table 4. The concepts are then scored a rating of 1 to 10 on each. It must be noted that these scores are quite subjective, and sometimes have to be determined based on the probability of meeting the criterium. The criteria are based on the requirements that have been established and are a balance between user-centric desires and more practical requirements.

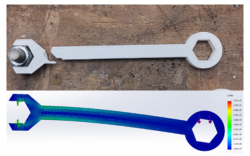
Table 4: Weighted Objectives criteria

Criteria	**Weight**
Incorporates elements that enhance 'wantivation'	30
Facilitates physical engagement with statics	25
Overall feasibility	20
Cost	15
Scalability	10
	100

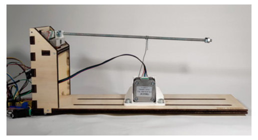
Now, the three concepts are scored. The result is shown in Table 5. The cantilever bending test concept has the highest score and is chosen as the concept to continue with. The concept needs further development and some exploration is needed. This concept already has the recommendation to find a way of making the counter moment in the support tangible.

Table 5: Weighted Objectives result

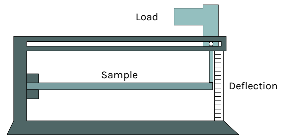
1. FEM + 3D prints



2. FBD machine (beam)



3. Cantilever bending



Criteria	1. FEM + 3D prints Score	1. FEM + 3D prints Total	2. FBD machine (beam) Score	2. FBD machine (beam) Total	3. Cantilever bending Score	3. Cantilever bending Total
Wantivation	7	210	6	180	7	210
Physical	6	150	8	200	8	200
Feasibility	7	140	5	100	8	160
Cost	8	120	7	105	6	90
Scalability	8	80	7	70	7	70
		700		625		765

Time for embodiment!

7.6.1 Deeper look into choice

In chapter 2, it was decided to leave stress and strain (mechanics of materials) out of scope, as it already has an experiential machine, the LETT. The now chosen concept however is actually focusing on this subject, but with a different intent and different topic. The LETT focuses on a different aspect (tension and compression), covering one-dimensional stress states. With the LETT, students stress material until it fails, meaning the stress is exceeding the yield strength (plastic deformation) until reaching the fracture point. This is better explained when taking a look at a typical stress-strain diagram (Figure 27). The new concept, however, addresses bending, which is a multidimensional stress state, and could therefore easier be related to statics. It could even function as a bridge to the NVM lines. Calculating the bending of beams with the deflection formulas is about elastic deformation, meaning the stress is not exceeding the yield strength, staying in the elastic region.

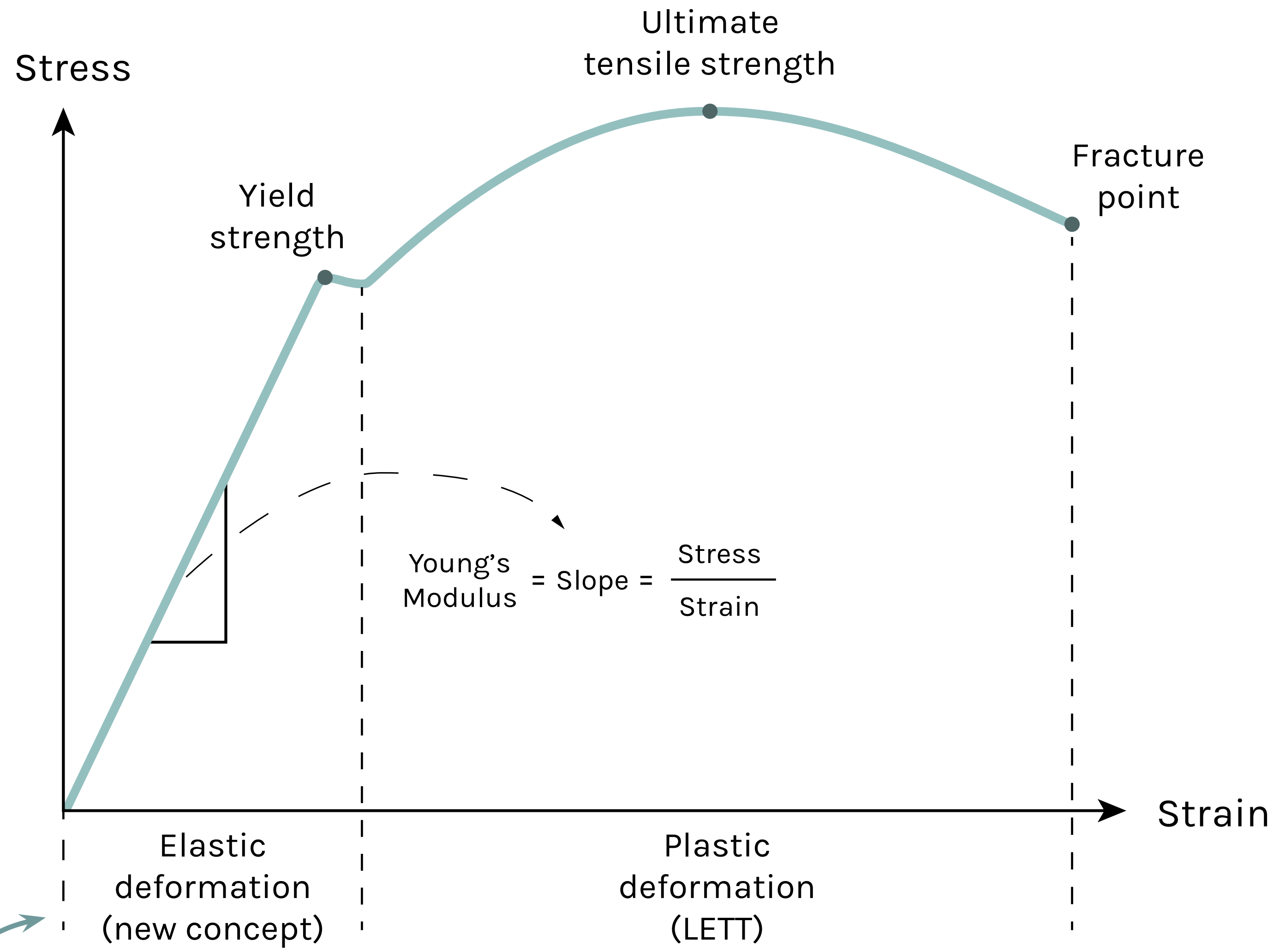


Figure 27: Stress-strain curve of unspecified ductile material

As visible in Figure 27, the new concept fills a "knowledge gap", therefore still being an innovative solution. In further development, presented in the next chapters, the LETT is taken as inspiration. This way, the final design will seem to be from the same "family". This could help students see the relation between this device and the LETT.

Choosing to create a machine similar to the LETT, but now for testing the bending of cantilever beams, leads to the very basic concept shown in Figure 28. It also includes a basic solution for the wish to make the counter moment more understandable.
The concept's basic principle is a device in which a sample of material or part can be fixed on one end and a load can be applied on the other end, or anywhere else on the beam. The fixed end has a torque sensor, which helps make the normally quite abstract reaction moment more concrete. This could serve an educational purpose in potential assignments that come with the machine. The deflection of the free end, or any other point, can be measured with a distance sensor.

The torque sensor might not be the only possibility to let students better grasp the existence of a counter moment. However, in the time span of this project, it was chosen to continue with this decision as it is an accessible solution. With integration in assignments, it has the potential to still serve this purpose.

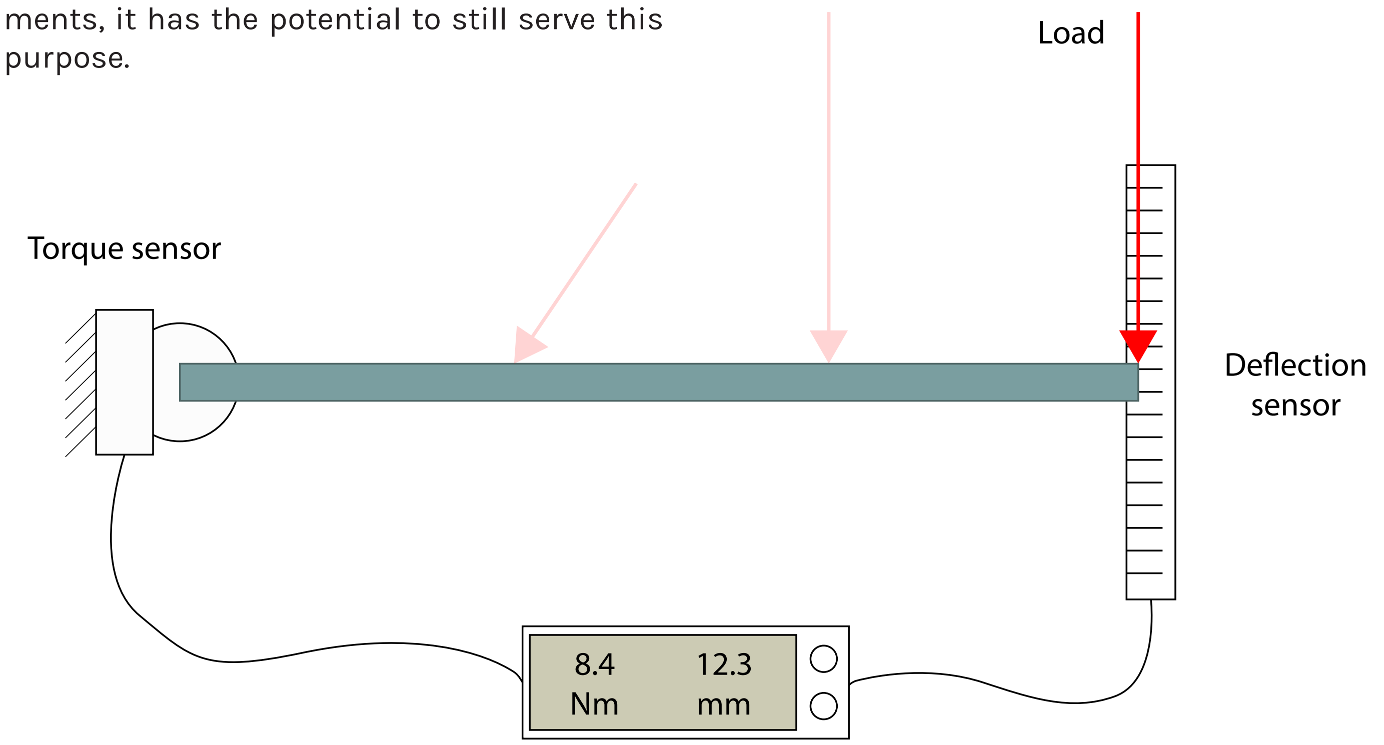


Figure 28: Cantilever bending test principle concept

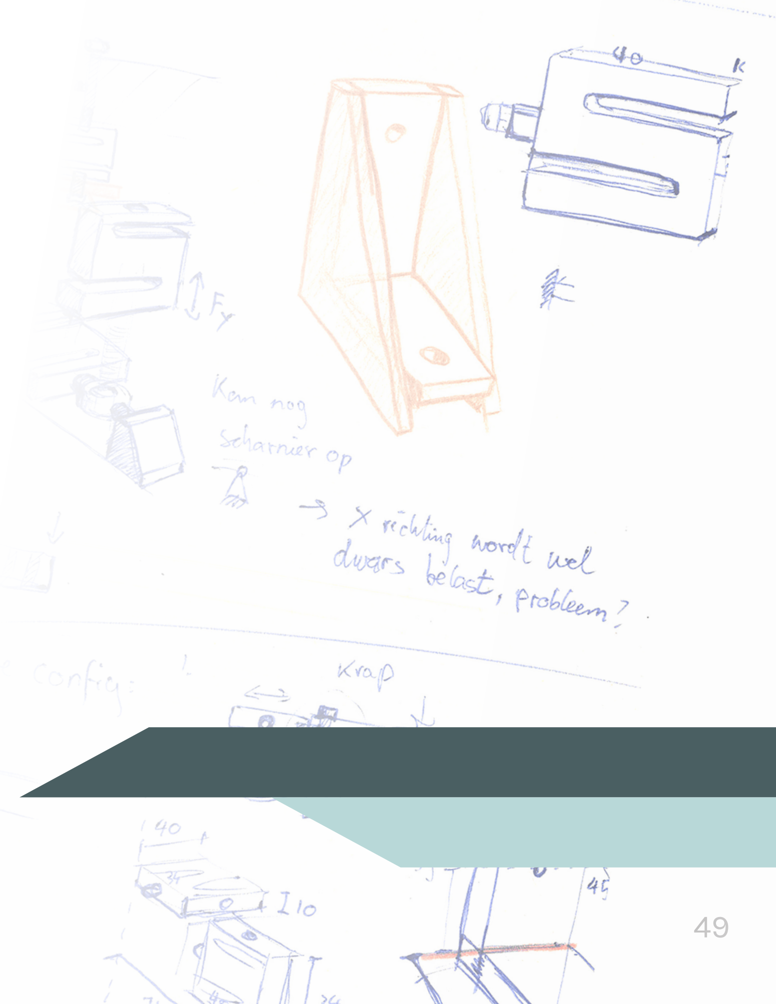
7.6.2 New requirements

This concept choice also comes with additional requirements that are more specific to the prototype-to-be. These are listed in Table 6. In the following chapter, the embodiment of the concept is elaborated on.

The requirements R11, 13 and 14 are chosen to function as guidance during development. The concept does not have to be a highly accurate measurement device, as its purpose is purely educational. To be usable though, the user needs to be able to get at least logical measurements.

Table 6: New requirements

R11	Load application must be possible in steps of 1 N
R12	The design must provide a way of visualising the reaction moment in cantilever beam supports
R13	The design must provide a way of measuring beam deflection with a resolution of 1 mm
R14	The maximum relative error between expected and measured deflection values must be 30%
R15	The design must allow users to fix different materials
R16	The design must allow users to fix different profiles



8

Embodiment

In this chapter, the embodiment of the concept from Figure 28 is presented. Different options for the necessary parts are discussed and final choices are made. These options have mostly been generated by using How-To's. This is a method especially suitable for creating multiple ideas for a problem or function and comes from the DDG (Van Boeijen et al., 2017a). The final Proof of Concept is presented in chapter 9.

The main parts that are highlighted here are the configuration of the prototype, its frame, the torque sensor, the deflection sensor, the way the material can be fixed in the machine and a means of load application. They make up the basic design of the prototype. Furthermore, there are other parts that help the setup function, which are also discussed in this chapter.

8.1 Configuration

There are different configurations possible and different ways to apply a load. In Figure 29, three options are shown. The third setup is the most similar to the LETT.

The first uses a motor that winds a wire that can be connected anywhere on the beam. Running it through a series of pulleys makes it possible to apply the load at different angles. The second sketch has the same principle, but the motor is on the bottom, simplifying the setup. This way, the bending is only in downward direction, which is also the way cantilevers in exercises often bend. The third configuration uses a linear actuator that grabs anywhere on the beam, making it possible to push or pull up and down. Applying the load is a little more difficult this way as the whole actuator has to be turned. In all cases, it is not clear how much force is applied exactly and it is hard to do so without a sensor. However, this could technically be derived from the moment that is generated and sensed by the torque sensor.

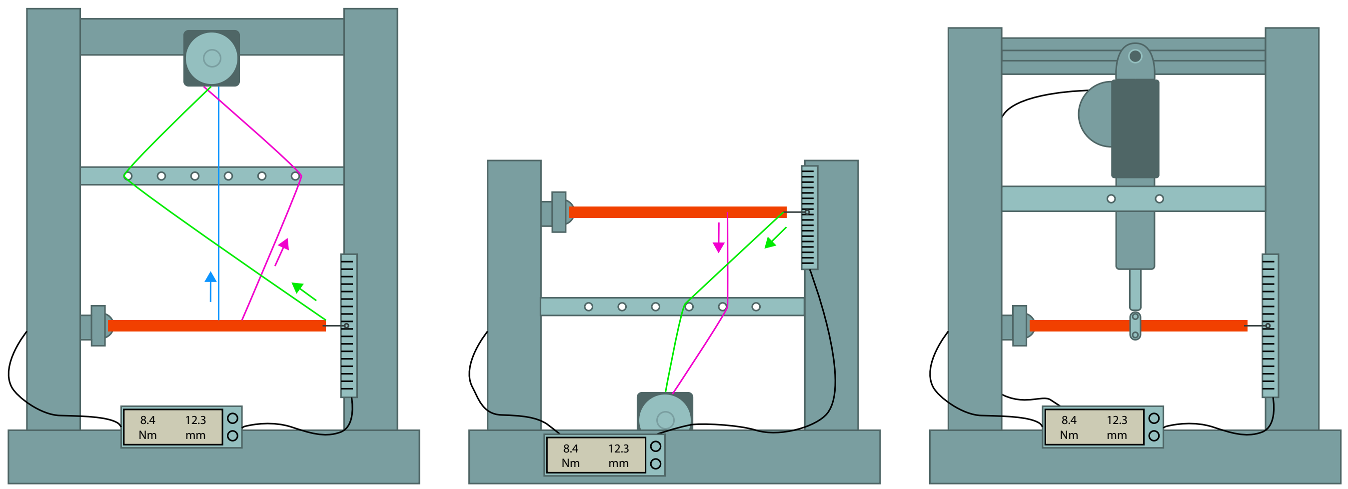


Figure 29: Different configurations and solutions for embodiment

8.2 Frame

For the frame of the machine, aluminium extrusion profiles can be used. These profiles are 50x50 mm and are exceptionally suitable for projects like this, as they allow for easy modifications. The extrusions come with T-shaped slots. Special nuts can be fitted in these slots and using M6 and M8 hex bolts it makes it easy to connect the extrusions together or fit other parts to them. The LETT used the same type of profiles, and due to their wide spread availability they are a reasonable choice. This availability increases the scalability of the experiential machine.

Their main disadvantage is their price. The 50x50 mm profiles used for this project were lent by the Applied Labs at the IDE faculty. This size starts at around €20 per metre when bought online. At this stage, it is unsure if 50x50 mm is required for the device. There are smaller sizes available as well, like 40x40, 30x30 or 20x20 mm. In evaluations, the design could be tested on size, which will most likely result in lower costs.

In the final Proof of Concept, these profiles and accompanying connection components are used (Figure 30a). If the prototype will be iterated on in the future, the extrusions also allow for easy modification. Besides, the LETT has the same look due to these profiles. This makes the EDA and the LETT look like they belong together in the same 'product family'.

Figure 30b and c show the connection pieces that are most used in the frame. The piece in b can be used to bolt parts to the frame or use corner connection pieces to connect two extrusions. The part in c is specifically meant to make a blind connection between two extrusions.

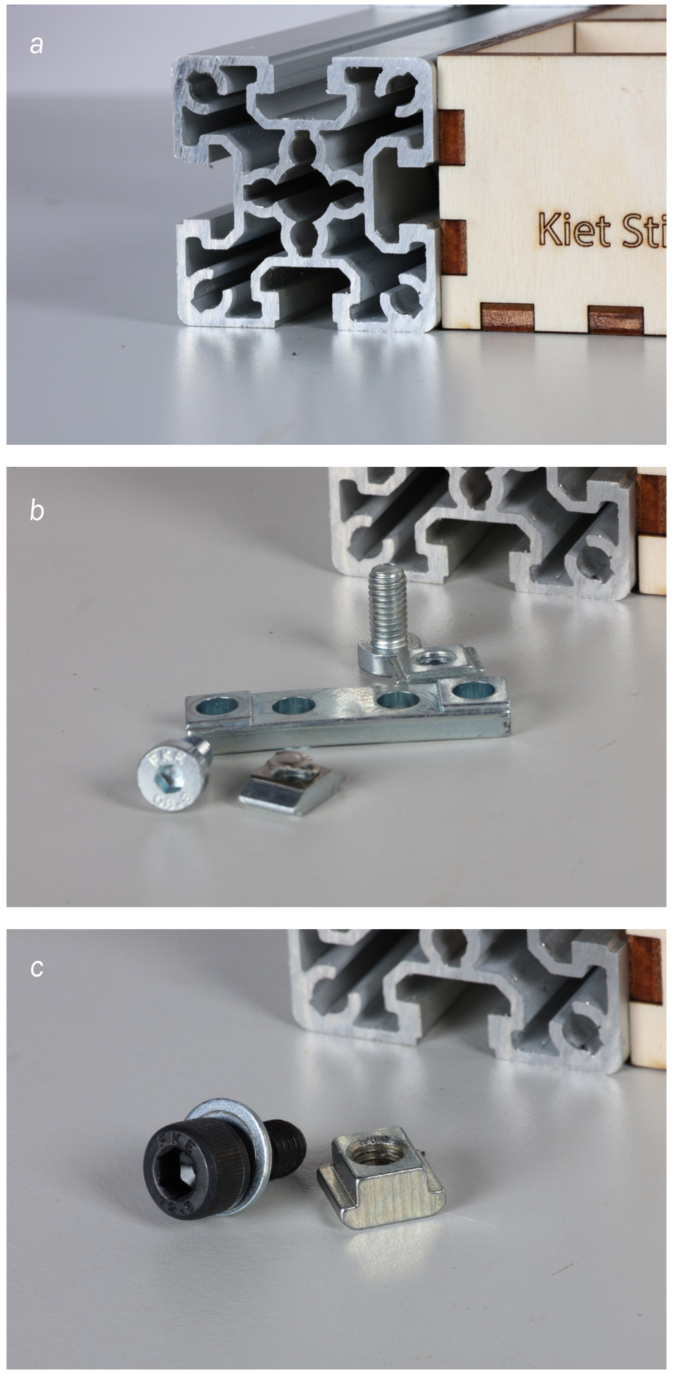


Figure 30: Aluminium extrusions and common connection pieces

8.3 Measuring torque

The created concept has a torque sensor on the fixed support. This sensor displays the moment (in N.m) that is created by the load on the cantilever beam. It is essentially not required to have this sensor if someone would just do bending tests with material, but it is included for educational purposes. An option for this sensor is a digital torque wrench adapter (Figure 31), used to turn a normal socket wrench into a digital one that can be used to torque bolts to certain specifications. Sensors like displayed cost €40 to €100.

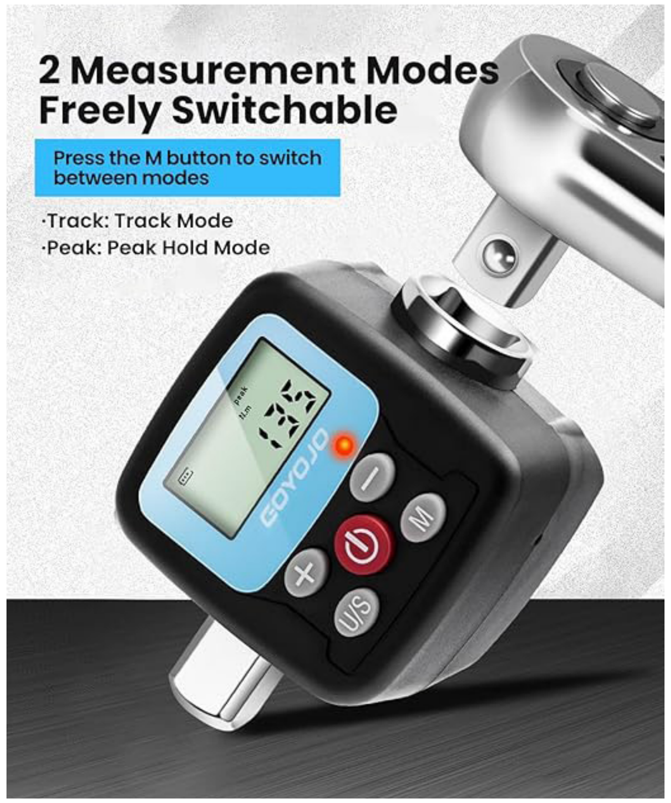


Figure 31: GOYOJO digital torque wrench set (GOYOJO, n.d.)

Other sensors were considered as well, for example industrial grade static torque sensors like the one shown in Figure 32. These sensors are accurate and allow for connection to laboratory measurement equipment. They could possibly also be connected to an Arduino, for further integration in the machine. However, these types range from €150 to €1000 or more and would take significantly more time and effort to setup.

Figure 32: Static torque sensor (Lorenz Messtechnik GmbH, n.d.)

Besides this, the digital adapter has ½ inch standardised connections for wrenches. This makes it easy to create a connection that fits well on either side of the adapter: one side is connected to the frame of the machine and the other has the fixture for the material samples.
Furthermore, there were 4 options to choose from with the adapter considering range and precision. The adapter with the lowest range (0.9 - 30 N.m) is best, as this one also has the best precision (0.01 N.m versus 0.1 N.m). This range is sufficient for the application.

Due to this lower pricepoint and the standardised connections, the digital torque wrench adapter is used in the final design (Figure 33).

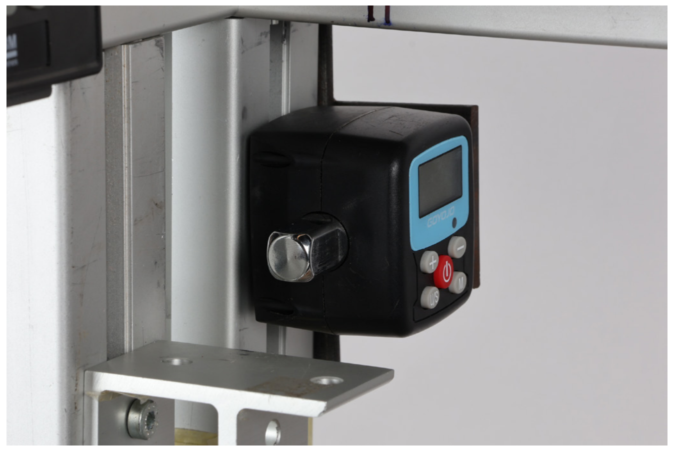


Figure 33: The torque sensor in position

The torque sensor needs to be connected to the rest of the machine. A way of doing this is modifying a torque wrench and using its standard ½ inch connector. Another option is creating a bracket that clamps the whole sensor to the aluminium extrusions with its plastic body (Figure 34).

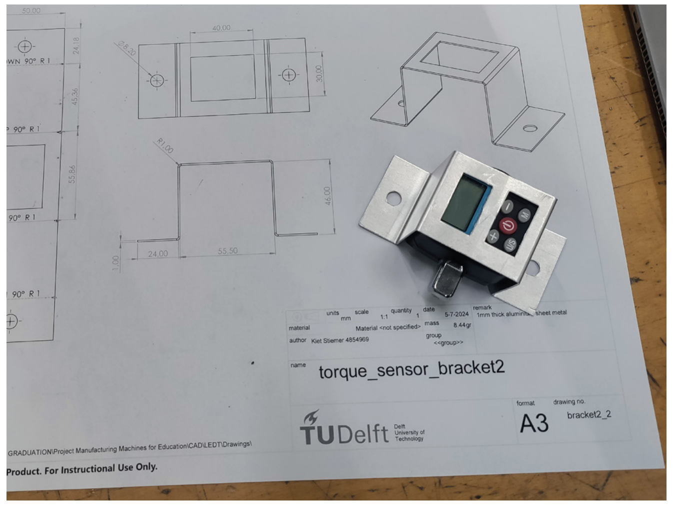


Figure 34: Aluminium bracket for sensor

With this bracket the torque is transferred through a part that is actually not made for it. This might not influence the measurements, but to make the sensor last long it would be better if the torque is transferred through the dedicated wrench connection. The body should be free, and the wrench-side of the adapter should be fixed. In the final Proof of Concept, this is implemented with a custom steel holder, shown in Figure 35.

Figure 35: Custom steel holder

8.4 Measuring deflection

Multiple options were considered for this part of the machine. There is a difference between options that monitor the deflection constantly while applying a load and methods that measure before and after applying a load, subsequently taking the difference.

With an Arduino and a Time-of-Flight laser sensor it would be possible to measure constantly and contactless. The advantage is also that this sensor could be mounted in custom ways, fitting the machine. The downside is that it requires specific code to get a consistent and accurate reading, without noise.
To still tryout this measurement type, a laser rangefinder was used. It is possible to get consistent readings with this tool, but the accuracy is only 1mm. Both of these methods have the problem that they need a good surface to reflect on, which is not always the case with small profile beams, making this option less feasible.

A non-contactless way was tried with a digital dial gauge, like in Figure 36. It offers high precision and could be used to measure while applying a load.

Figure 36: Digital dial gauge for deflection measurement

Its disadvantage is the low range, they are available from 0-12.7mm to 0-50.8mm. These types are also spring loaded internally, meaning they will apply a load on the beam on top of the 'normal' load that the user applies. This makes measurements less accurate and harder. Finally, it is also fiddly to position this device correctly.
Another continuous method involves using a digital ruler attached to the beam at the measurement point. This type, utilised in the LETT, is inexpensive, easy to install, and can be connected to an Arduino (Welling, 2014). However, it does introduce physical resistance, which could affect deflection measurements. Since the applied load is not significantly greater than this resistance, this method is not ideal. Frictionless alternatives exist, but they are very expensive.

Figure 37: Digital ruler (HBM Machines, n.d.)

The digital ruler, like in Figure 37, could also be used in a before-and-after method. This way it would be possible to still get accurate results and it can be easily fitted to the machine.

As the load application method is chosen to be manual, the before and after measuring method is more suitable. Therefore a digital ruler is used in the Proof of Concept, with which the user has to measure the height of the neutral axis of the beam before and after bending. It has a clear display with intuitive buttons, plus the function to "zero" the ruler. This is ideal when taking readings. The ruler is installed on the right side of the machine (Figure 38), with the display on the left side (Figure 39). This way the display faces the same way as the torque sensor.

Figure 38: Digital ruler installed

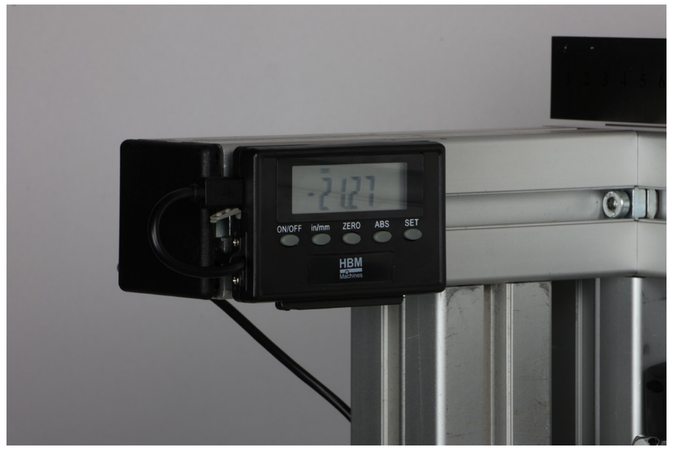


Figure 39: Ruler display

8.5 Fixing beam samples

Finding a suitable solution for this part is complex, as the requirement of being able to fix different samples and parts in the machine asks for flexibility. The torque sensor also imposes a challenge, as getting good readings requires all the torque to be transferred through the sensor. At the same time, this sensor and grip need to be completely fixed so that there is no slack affecting the deflection measurements.

As the torque sensor already has a specific connection, this does give some design direction. Essentially, it now requires a part that can connect material samples perpendicular to this like shown in Figure 40.

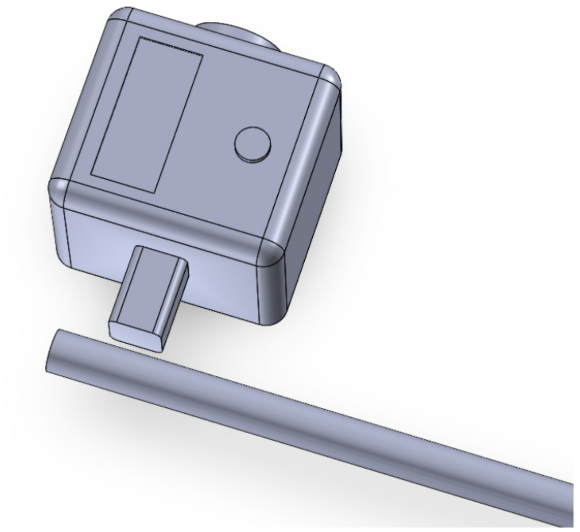


Figure 40: Perpendicular sample to sensor

An existing type of adapter is the adjustable torque wrench adapter from Figure 41. This was taken as inspiration for some prototypes.

Figure 41: Adjustable torque wrench adapter (Motion Pro, Inc, n.d.)

One prototype is shown in Figure 42. It connects by snap fitting to the sensor and uses three bolts to fix the material in place. It is also important that the material is as centred as possible, which is possible this way.

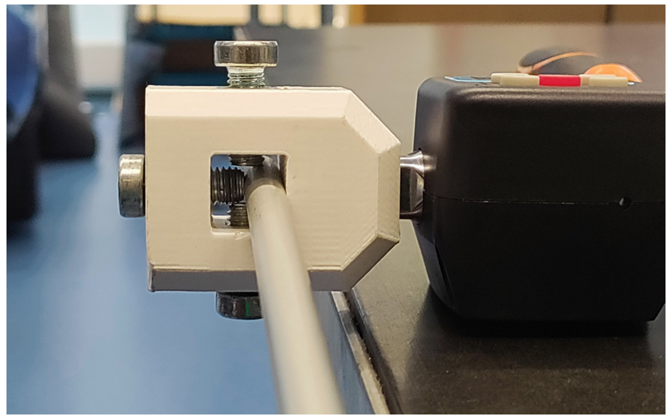


Figure 42: Grip number one

The problem with this one is that some movement in the horizontal plane is still possible, as the material kind of hinges around where the bolts touch it. The second iteration prevent this a lot better and uses only two bolts (Figure 43).

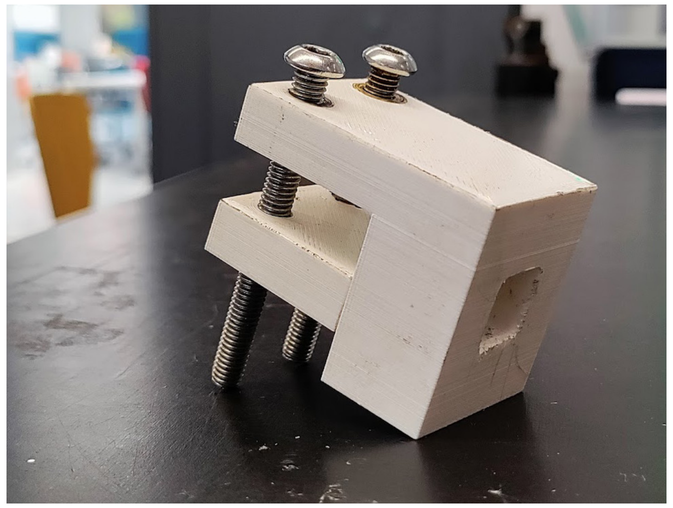


Figure 43: Grip number two

In the final application, the grip should be made from metal as no flex is tolerable. The last prototype uses the existing socket connection by adapting a normal hex bolt socket to this application. In Figure 44 is shown what this looks like. This design is easily swappable for bigger and smaller or different versions and creates a strong connection.

Figure 44: Final grip prototype

The adapted wrench socket works well for a small profile, therefore another bigger one is created so that it is possible to fit larger profiles as well (Figure 45). This is implemented in the final Proof of Concept. The larger one fits small profiles as well, but using the smaller one in those situation prevents the sample from being far from the centre.

Figure 45: Grips in two sizes

The grips are installed on the torque sensor through the standard connection, which works with a snap fit (Figure 46).

Figure 46: Large grip installed

8.6 Applying load

In the situations with a cantilever and a force as described in chapter 5.2, often a point load is used. This is the main situation that the machine is used for, although it could at some point also be possible to apply a distributed load or maybe even a moment.
Now, the way this point load is applied has different options. The main two categories are manual or automatic: with a manual method, the user applies the load using e.g. weights, their hands or a winch. When using an automatic method, devices like pistons, motors or linear actuators could be used. The LETT uses an Arduino-controlled linear actuator (Figure 47) for the load application.

Figure 47: Linear actuator DTL100 (LOUIE, n.d.)

Using a similar product for the final design is possible and it would allow for precise force application. When Arduino would be used for full integration of load application plus deflection measurement, the machine could even have a similar Graphical User Interface (GUI) as the LETT. This could potentially improve the usability of the machine.
At the same time, the linear actuator in the LETT always has the same position and angle. This is ideal for typical tensile testing, however for a cantilever bending test it would be better if the user has freedom in positioning the load. This could also be possible with a linear actuator on rails and hinges. However, this does complicate the machine quite a lot.
A manual method is using a hanger with slotted weights, like shown in Figure 48.

This is a method commonly used in physics and engineering experiments or in labs to calibrate instruments. Using them is intuitive and they are readily available and inexpensive. They could be hung on the sample on any position. The downside is that they cannot be positioned at an angle and the user also has to take the hanger's weight into account. Lastly, a manual method is also prone to more mistakes.
If the sample beam bends, the hanger might slide off if it is hung directly on the beam. Therefore a piece that clamps on the sample is required too, on which the hanger can hang. Hoseclamps could be an option for this as they are easy to tighten and loosen, but a custom piece is also possible.

Although it would be interesting to be able to apply precise loads in small steps on the beams, it is decided to keep this relatively simple and manual. This makes playing around with the machine even more "hands-on". A hanger with different weight sizes is provided with the machine.

Figure 48: Hanger with slotted weights (*Slotted Weights on Hanger*, n.d.)

8.7 Other parts

The concept needs a few other components that improve the performance or help with convenience.

8.7.1 Guiding board

This addition to the final Proof of Concept is based on the user tests (chapter 10.2). The tests showed it is hard to accurately position the digital ruler and it was suggested to use a background to guide the user. This is shown in Figure 49.

Figure 49: Guiding board with horizontal and vertical ruler lines

The guiding board is made from acryl and is cut and engraved with a laser cutter. The choice for transparent acryl is deliberate: this way the reading of deflection is possible from the back of the prototype. This is actually easier than from the front, especially when a student needs to read the height of a position on the beam that is not the free end.

Besides this, the transparency and double-sided use has another effect. It makes it easier to stand around the machine, instead of needing to stand with multiple students on one side. This aids interaction, as students are now facing each other more. Stefan Persaud calls this the "Campfire Effect".

8.7.2 Storage and accessories

The storage compartments with tools like a separate ruler, screwdriver, allen keys, small spanner, the grips, hose clamps and the weights and samples (Figure 50 and Figure 51). This is inspired by the LETT, which also has laser-cut compartments.

Figure 50: Front storage compartment

Figure 51: Rear storage compartment

Hose clamps to secure the hanger with weights to a sample (Figure 52), in case the sample flexes so much that the hanger would slide off.

Figure 52: Hose clamps

8.7.3 Support

An extra support opposite of the torque sensor, to rest the grip on (Figure 53). This prevents sagging of the sample and ensures it is horizontal when measuring.

Figure 53: Additional support

Final Proof of Concept

In this chapter, the final design is presented. It also contains some technical data, cost and a section about the accompanying educational module.
In Figure 54 the design of the machine is shown. Proceeding this, a step-by-step explanation of the operation procedure is presented.

9

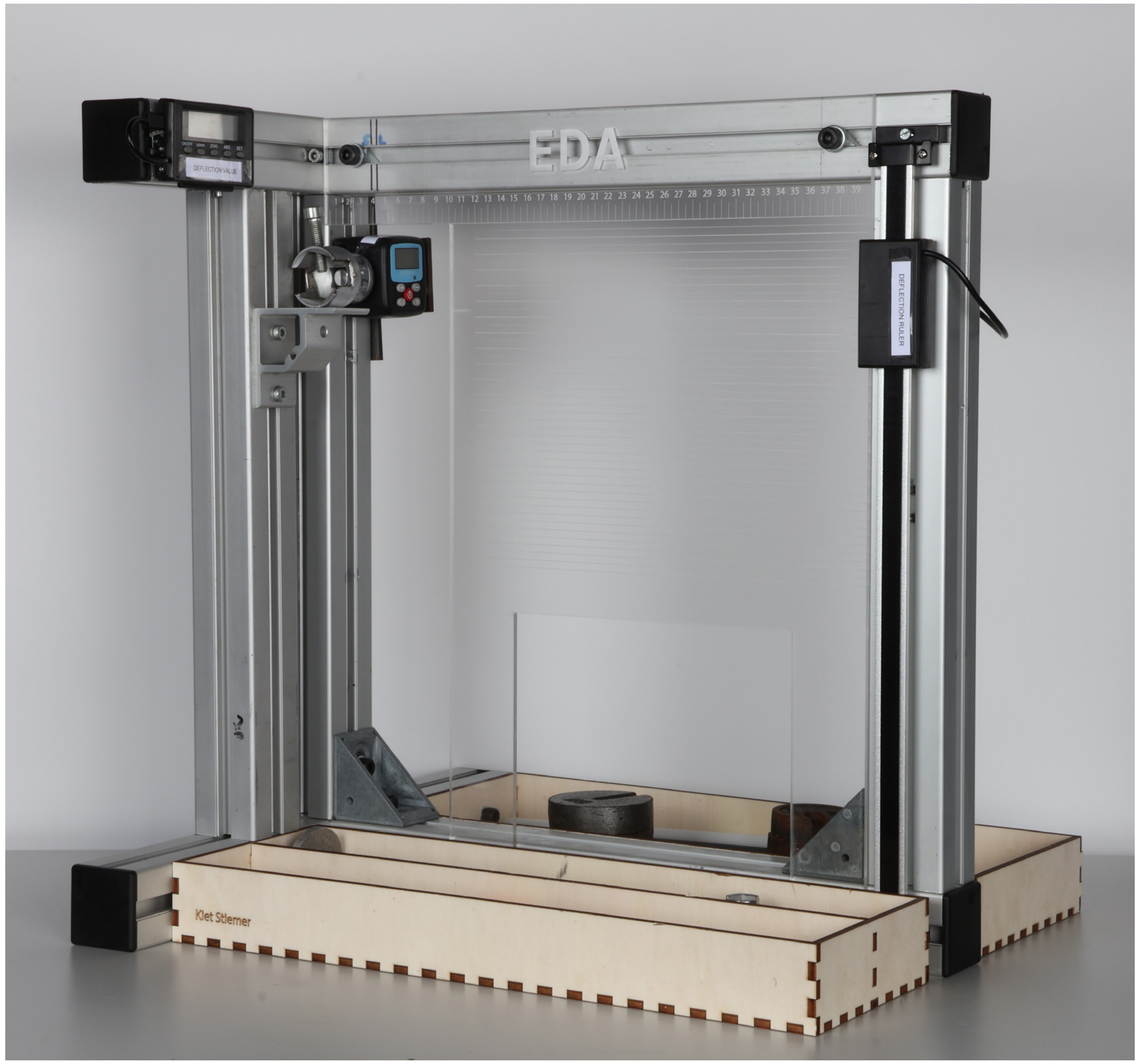


Figure 54: Final design of the EDA

The device is called the Educational Deflection Analyser or EDA. Its goal is to offer first year students a hands-on way of experiencing basic mechanics of materials principles and improving the understanding of statics. The EDA's design is both visually intriguing and encourages curiosity, inviting students to engage with it.

Equipped with a variety of developed parts and accessories, the EDA enables students to perform beam deflection measurements in a workshop setting. Through these exercises, they will not only learn about relevant material properties but also develop their designer intuition and insight, which will be invaluable in their future design projects.

9.1 Operating procedure

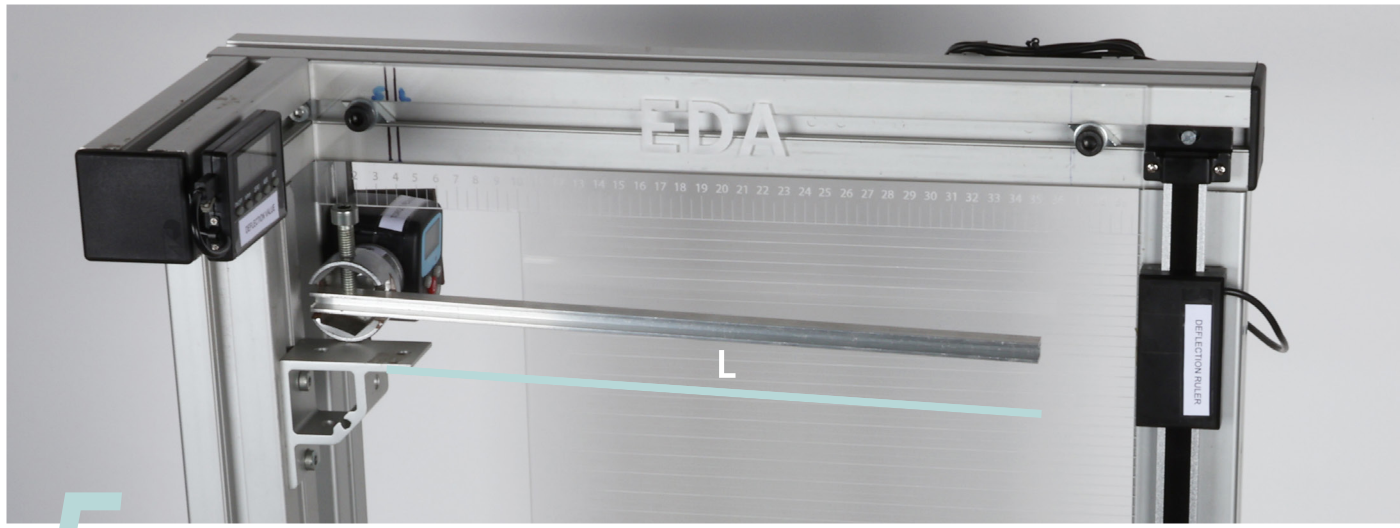
In this section the basic operating procedure of the EDA is shown. It provides an overview of the steps that need to be executed to perform a deflection measurement.

1 ***Figure 55***: Choose a sample from the provided material

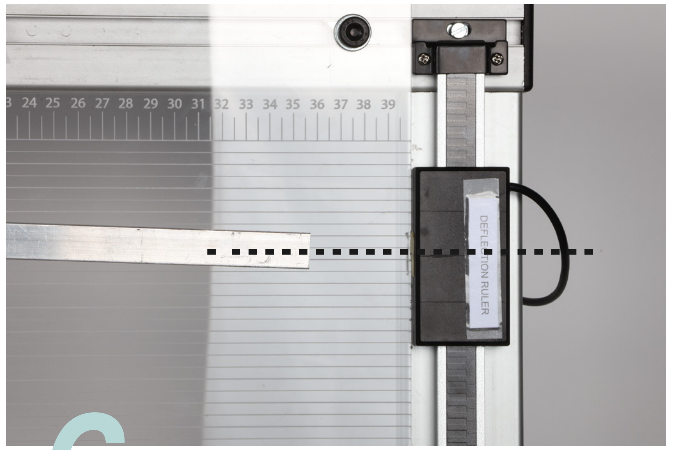
2 ***Figure 56***: Choose a fitting size grip and install it on the torque sensor

3 ***Figure 57***: Start the digital ruler and torque sensor

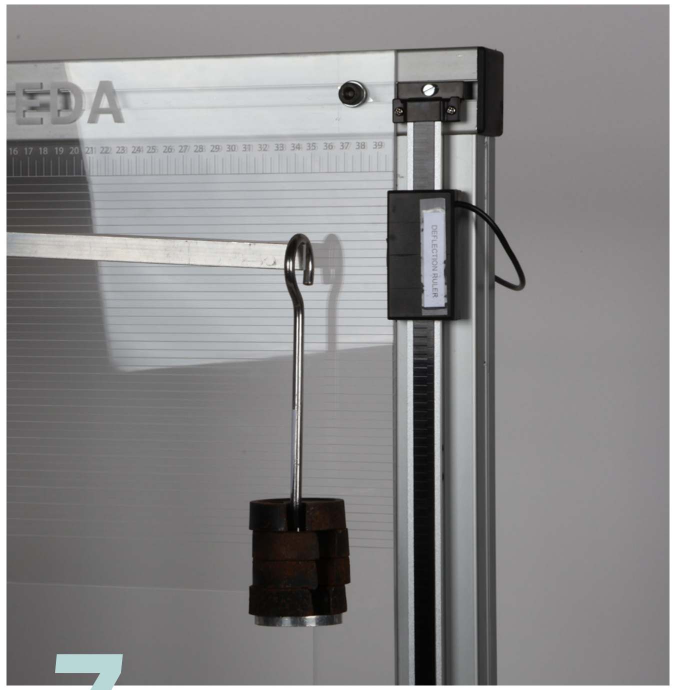
4 ***Figure 58***: Fix the sample in the grip with a hex key



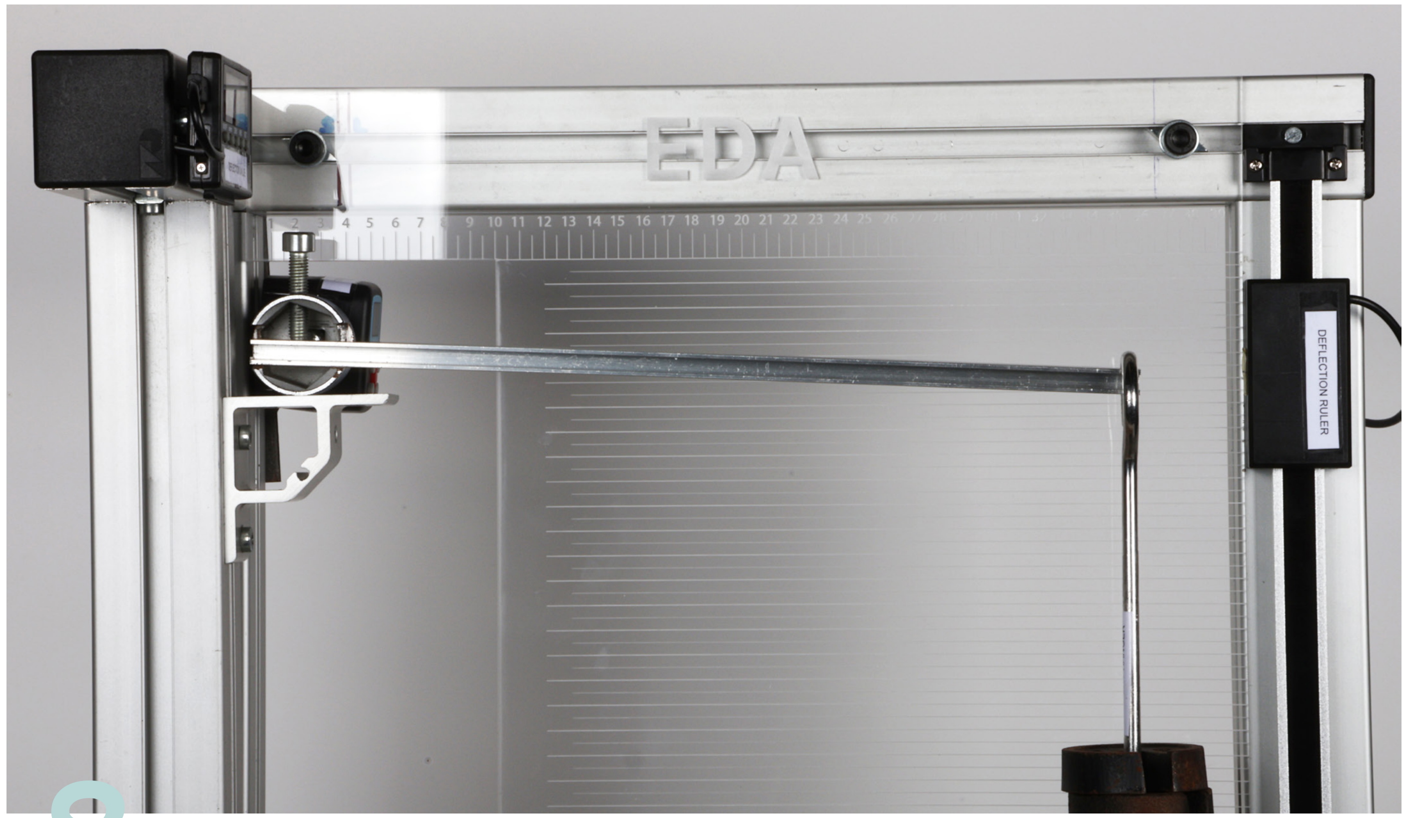
5 ***Figure 59***: Choose a position to apply the load and measure the length of the beam from the grip to the point of load



6 ***Figure 60***: Position the digital ruler on the initial position of the sample in rest, zero the ruler



7 ***Figure 61***: Put the hanger on the sample on the chosen position and add weight



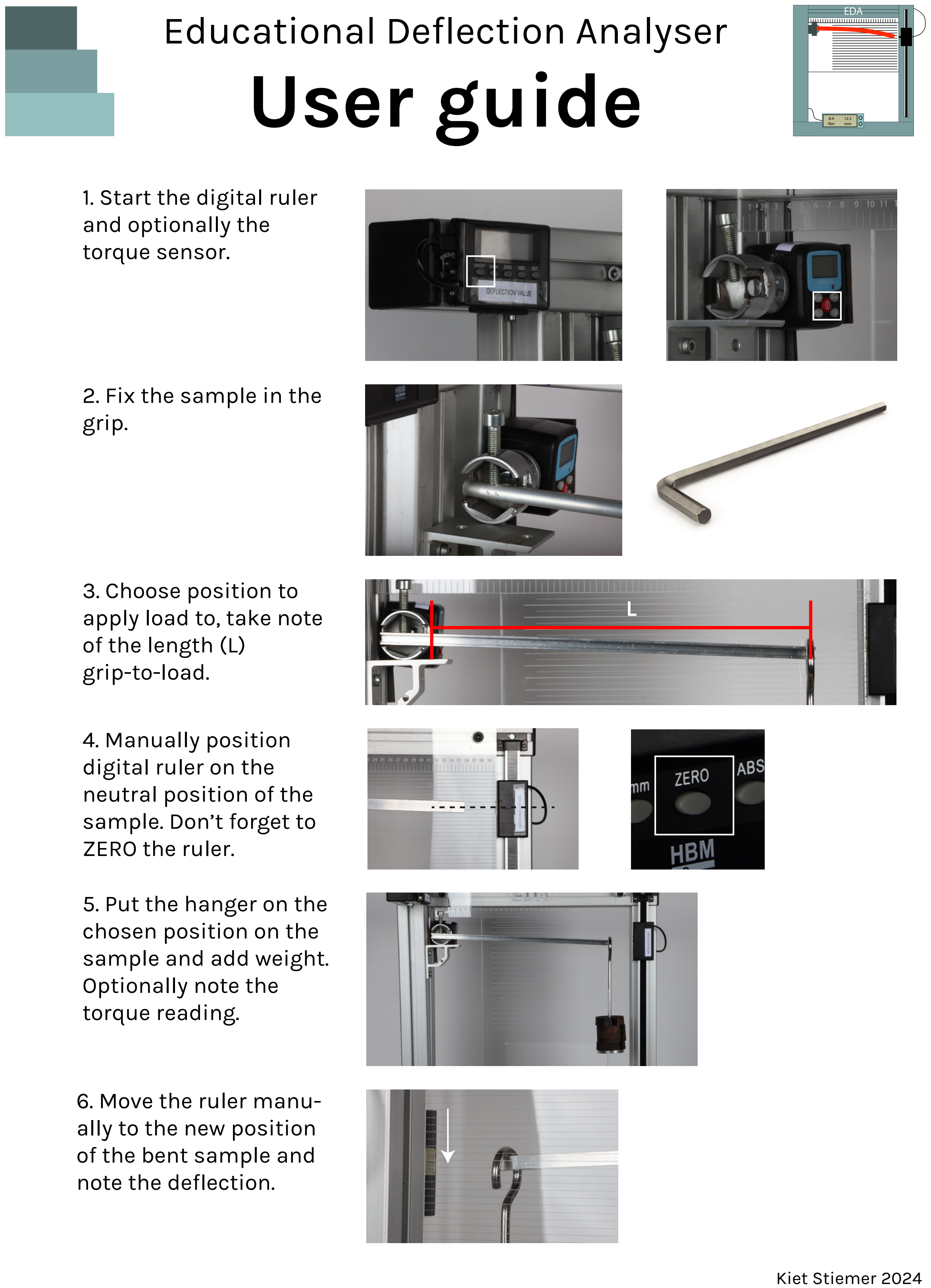
8 ***Figure 62***: The sample will now bend as shown, note the torque reading

9 ***Figure 63***: Move the digital ruler to the lower height of the sample and note the deflection

10 Try different loads and positions and note the effect. Try different samples as well.

9.2 Instruction manual

The EDA comes with a simple quick start guide for users. It only shows the basic steps to perform a measurement and is deliberately only one A4 sheet. It is shown in Figure 64.



Educational Deflection Analyser

User guide

1. Start the digital ruler and optionally the torque sensor.

2. Fix the sample in the grip.

3. Choose position to apply load to, take note of the length (L) grip-to-load.

4. Manually position digital ruler on the neutral position of the sample. Don't forget to ZERO the ruler.

5. Put the hanger on the chosen position on the sample and add weight. Optionally note the torque reading.

6. Move the ruler manually to the new position of the bent sample and note the deflection.

Kiet Stiemer 2024

Figure 64: Basic user guide for the EDA

9.3 Dimensions

The dimensions of the EDA are important, as the goal of the assignment is to have desktop-size experiential machine. This means it has to fit on a standard desk in a studio at the IDE faculty and not weigh more than 10 kilograms (R19 and 20 in Program of Requirements).

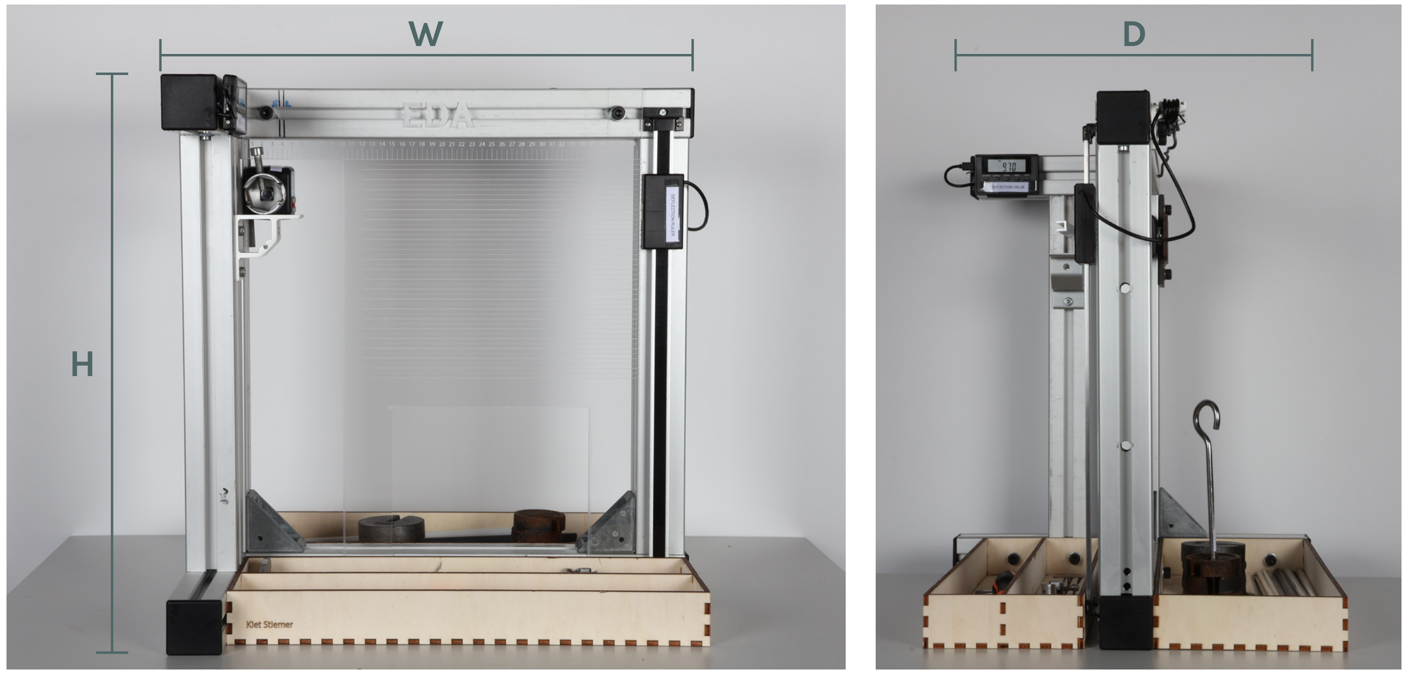


Figure 65: Front and side view of the EDA

In Figure 65, the dimensions height (H), width (W) and depth (D) are indicated. They have the following values:

- H: 52.5 cm
- W: 50 cm
- D: 43 cm

With these dimensions the EDA easily fits on a studio desk.

The weight of the EDA is also important. The experiential machines are transported on trolleys and carts through the faculty, but humans still need to lift them from storage on carts and then on tables. The EDA has an empty weight of 10 kilograms, and the accessories (including weights) are another 3 kilograms. If the size of the aluminium frame profiles gets decreased in future iterations, the weight can become significantly lower, to meet the requirements.

9.4 Cost

The costs of the EDA have been estimated. In Appendix 14, an overview can be found. The price of the EDA is around €230 for the materials. When labour costs are included, it comes down to €290. Labour costs are a rough estimate and in this case it is assumed the faculty would employ a student assistant to build the devices or instruct a current workshop student assistant to do so, for €20/hour.

It must be noted that for the prototype, often single parts were ordered through mail. This frequently means shipping is quite expensive, and when ordering larger quantities these costs go down per manufactured EDA. Furthermore, the frame pieces make up a large part of the cost. This share could be decreased if smaller profiles are used and/or possibly ordered in large quantity. The other relatively expensive part is the torque sensor that is used in the EDA (€59,99). If in future iterations costs need to be cut, more research toward this part should be conducted.

Concluding, the requirement of a maximum of €500 per device (R4) is met well within margin. In the future, the EDA might change quite a lot. Therefore this cost cannot be seen as final, but it is an indication.

9.5 Educational module

An important goal from the assignment is the need for an educational module, or workshop assignment proposal. As mentioned in chapter 2, the PFDC is used to come to an accompanying workshop assignment for the EDA. In Appendix 10 can be found how this cycle was performed. The proposed workshop structure from the PFDC (Figure 11) is used. The chosen workshop is related to real problems and design properties. It is also possible to give a more "plain" workshop, such a version is also shown in Appendix 10.

9.5.1 Workshop

The accompanying workshop has the following setup protocol:

Who: Student groups of 4 to 5 students
Where: A studio in the IDE faculty
When: One afternoon from 13:45 until 17:30
What: Provided per group is a table with chairs, the EDA including samples, some basic tools and measuring devices, whiteboard with markers and one large screen and aeroplane seat for the whole studio (see Figure 66).

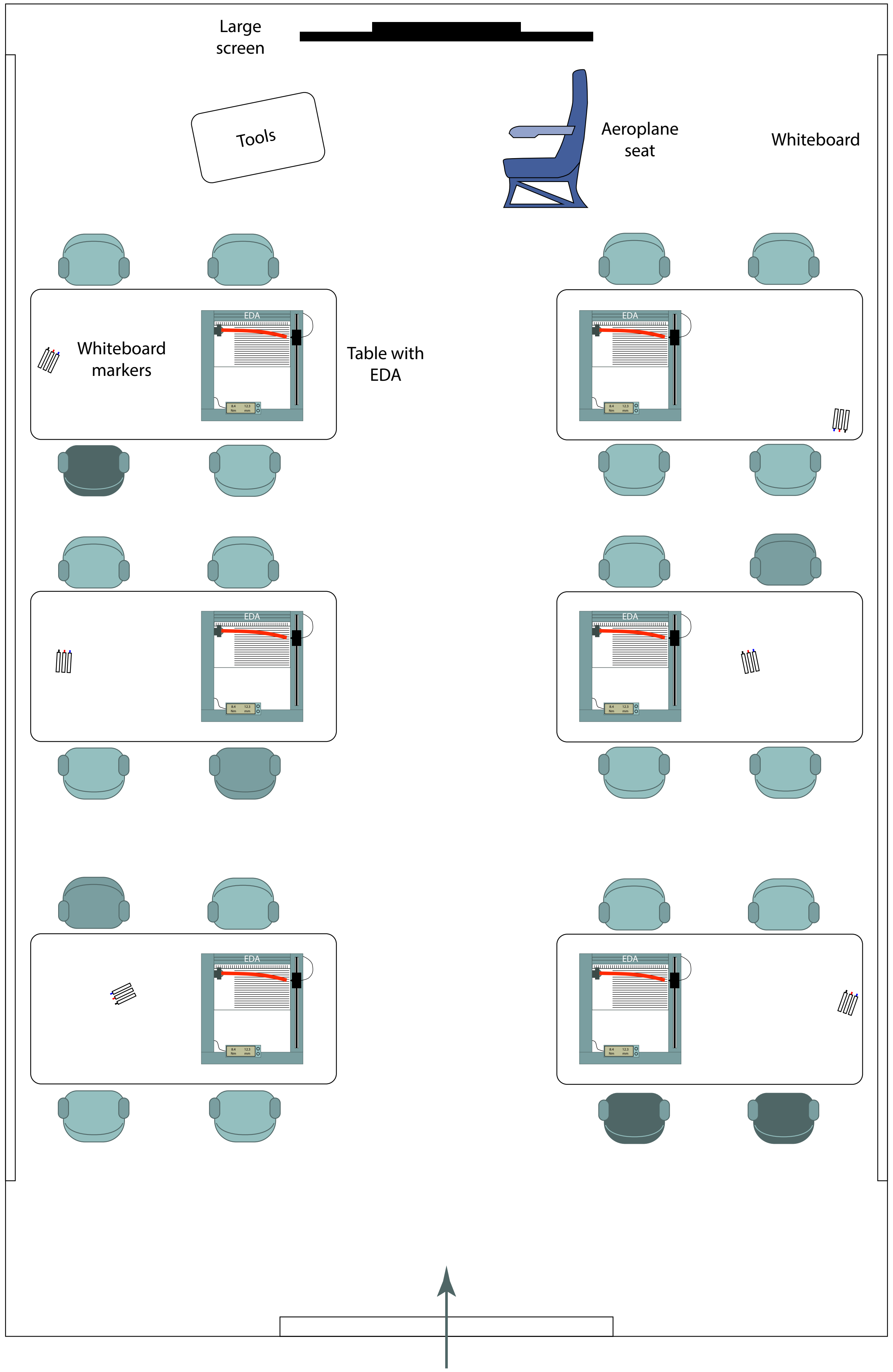


Figure 66: Workshop with EDA in studio

The workshop structure is as follows:

Prepare	• Formative exam, questions related to the lecture
Ideate	• Problem introduction: group of students is asked to find a sample that can be used in the construction of the armrest of an aeroplane seat. It needs to be as light as possible and resist the force of a large human's arm leaning on it • Guided brainstorm: brainstorm possible solution strategies with the group, how to find variables and constants that have influence on the bending of the armrest • Select and try: the group selects an approach and gets to work with the EDA • Share: the groups share their findings to the rest of the studio
Ideate	• Direct instruction: video with explanation of the deflection formula and its variables and constants is shown, emphasis on how to use this to your advantage • New assignment: the groups are now instructed to try to predict which sample is the best based on theoretical calculations and compare this with reality • Try again: the groups will now calculate the theoretic values. To do so, they need to measure the geometry of their samples and find the Young's modulus in Granta EduPack. To also find out which sample is the lightest, they can either weigh them or use the volume and density to calculate this
Evaluate	• Wrap-up: evaluate key findings: what is the optimal sample? Reflect on process and the role of the EDA

This workshop incorporates an element of realism, as the aeroplane seat is easy to relate to in use and the goal of it being as light as possible is understandable in the context of flying. This is beneficial for the motivation of the students, as relevance is important for the "wantivation". To elaborately test this workshop and approach, user tests with the correct target group must be performed. This is in a small version performed in chapter 10.3. Lastly, the assignment does not incorporate the moment sensor yet. This is a recommendation for further development, but a suggestion could be to focus on the joint of the armrest as well which has to resist the torque. Another option is to give the students tapered armrest designs with which bending moments can be taught, as the bending moment is the largest close to the fixed support and farthest away from the load.

This workshop could be deployed in week 5 (stress and strain), if the current UPE curriculum is considered. It is however interesting to also try the aforementioned inverted approach, where this workshop would be given at the start of the mechanics of materials phase. That would mean in week 3 this workshop is given, only after which statics and NVM lines are taught.

Validation

The final design has been tested in various ways. First of all, the actual measurements compared to theoretical calculations has been tested. Secondly, the usability of the EDA was evaluated in a user test and finally a user test with the target group is conducted.

10

10.1 Accuracy assessment

To test if a student can get accurate results with this device, expected values were compared with measured values. This way requirement R14 (maximum error of 30%) is tested. The expected values were calculated with the deflection formula from chapter 5.2. The tests were performed with 9 samples of different materials and profiles. Two profiles were tested in two different orientations, a rectangular profile and a U (channel) profile, making 11 tests in total. The Young's modulus of each material was taken from the software Granta EduPack 2023 (Ansys, Inc, n.d.), using the average of the indicated minimum and maximum. The other variables (force, length and moment of inertia) were calculated or measured.

The measured values were acquired in three tests. The first two tests the construction rangefinder was used with a resolution of 1 mm and two different loads were applied. With this device, the measurements were taken from a fixed position to the top of the beam where the load was placed. The third test an analog height gauge was used, measuring the position before and after deflection and subtracting the values. The difference is that with the latter the displacement of the neutral axis of the profile was taken, while the rangefinder measured the displacement of the top of the beam. This should technically be less accurate as when the beam bends, the place of the load moves horizontally inwards a little. The extremer the bend is, the more it moves. When the sensor keeps measuring the same horizontal position, the distance it measures is to a new position on the beam, a little outward from the point of load.

10.1.1 Findings

A relative error value was calculated by using $error = \frac{measured - expected}{expected} \times 100\%$. The full results are presented in Appendix 11. Here, we first discuss the main findings.

- The error differs greatly between profiles:

Table 7

Description	Deflection (mm)	Measured (mm)	Abs. error (mm)	Rel. error
Aluminium rod round	4.7	8	3.3	71%
Aluminium tube round	6.3	8	1.7	27%

- For the majority, the actual deflection is larger than the theoretical
  - Only for PVC the deflection is less, in all cases
- For the majority the difference between profiles in theory and practice is the same
  - e.g. aluminium L angle profile bends more than the sideways aluminium U channel profile, both in calculations and in measurements
- The error margin seems larger when the deflection is smaller, accuracy goes up with larger deflections:

Table 8

Description	F (N)	Deflection (mm)	Measured (mm)	Abs. error (mm)	Rel. error	Abs. Error 2 (mm)	Rel. error 2
Aluminium rectangle vert.	11.0	1.3	5	3.7	286%	3.7	277%
Aluminium rectangle vert.	20.7	2.4	6.3	3.9	158%	3.8	155%
Aluminium rectangle vert.	35.5	4.2	10.5	6.3	151%	6.3	149%

- This is also notable with the brass square, round steel and POM rods, which all clearly flex more than the other samples:

Brass rod square	11.0	57.5	64	6.5	11%	5.7	10%
Steel rod round	11.0	47.6	55	7.4	15%	6.8	14%
POM rod round	6.0	17.5	21	3.5	20%	3.2	18%

- The accuracy increases when the bending due to own weight is taken into calculation
- Surprisingly, the error is worse when measuring the neutral axis with the height gauge, seven out of eleven measurements have a higher error
- The absolute error is not larger than a few millimetre in most cases

10.1.2 Discussion

These accuracy tests show what and what not the EDA can be used for. It is very important to notice that it is hard to draw clear conclusions about the accuracy, as the measurements are compared to theoretical values that are partially based on assumptions. Therefore there is always the chance there are errors in the calculations. The theoretical deflection also relies on the length of the beam from the grip to where the load is applied. This length L is related to the deflection by the third power, meaning that a small error has great influence. In the current setup, it is however difficult to apply the load super precisely.
On the other hand, while the absolute error is relatively small in most samples, the relative error becomes quite substantial when the expected deflection is as small as 2 or 3 millimetres. This suggests that the factors influencing the measurements may not be directly related to the deflection itself but could be relatively constant.

The grip, being fixed on the torque sensor, has a little bit of play and the same goes for the connection of the sensor to the frame. Moreover, the torque sensor works with internal strain gauges, deriving torque from the little bit of strain that occurs when applying force. This all adds up to a little bit of possible rotation. Therefore, the sample has to be "pre-loaded" to get a correct initial position measurement, otherwise this slack is included in the measurements making them inaccurate. The longer the measured sample is, the more this error accumulates. This issue is shown in Figure 67.

Moreover, it is advisable to redo the evaluation without relying on the average of the Young's modulus values. Instead, the theoretical deflection could be calculated using the minimum and maximum values from Granta EduPack 2023, thereby establishing a range within which the actual measurements are expected to fall.
Concluding, the requirement for a maximum of 30% error is not met (R14). Even though the accuracy of the EDA is uncertain, the machine can still be used to find the difference between certain shapes and materials. This is valuable knowledge for students and they simultaneously learn about the relationship between force, distance, material properties and deflection. The user tests also confirm this, as discussed in the next section.

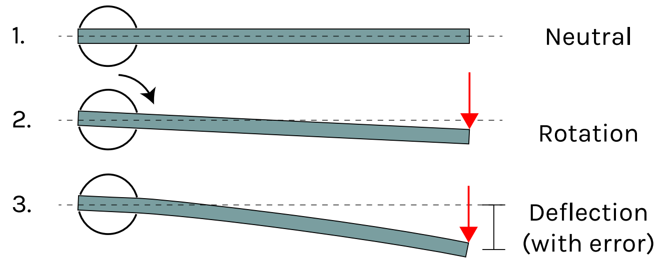


Figure 67: Deflection error caused by slight rotation of construction

10.2 User test: usability

For the user tests, a simple experiment is conducted. The objective of this experiment is to evaluate the basic usability of the EDA. The full plan can be found in Appendix 12. The test plan is aided by *Product usability evaluation* from the DDG (Van Boeijen et al., 2017c). It is important to notice that the educational value of the machine is not evaluated in this experiment, as this is only possible if the EDA functions well enough. As the experiment was low risk and anonymous, HREC approval (Human Research Ethics) has not been requested for this small test, but it has been considered.
Lastly, this evaluation is not related to a design requirement. The goal is purely to obtain insights for improvement of the design. A followup user test, concerning the target group, is conducted to validate requirements.

In the experiment, the participants got the assignment *"You are designing a chair and for the arm rest you have gathered different materials and shapes. Choose three samples and try to figure out which sample has the least deflection. Use the machine and accompanying Excel sheet"*. They were first asked to execute this assignment without any specific instructions about the machine. In a second phase, the machine was explained in detail and they were asked to do the assignment again. The goal of this two-phase setup, was to evaluate if the machine was intuitive to use.

After conducting a pilot test, three students participated in the experiment. A participant following the test is shown in Figure 68. The results can be summarised as follows: while the general concept of the device was clear to the students, and they understood the overall objective, the specific procedures for operating the device were found to be more complex. Consequently, it is necessary to provide a basic instruction outlining the functions and interactions of the various components to ensure correct use. At the same time, there should be room left for trial and error as the Productive Failure method is applied.

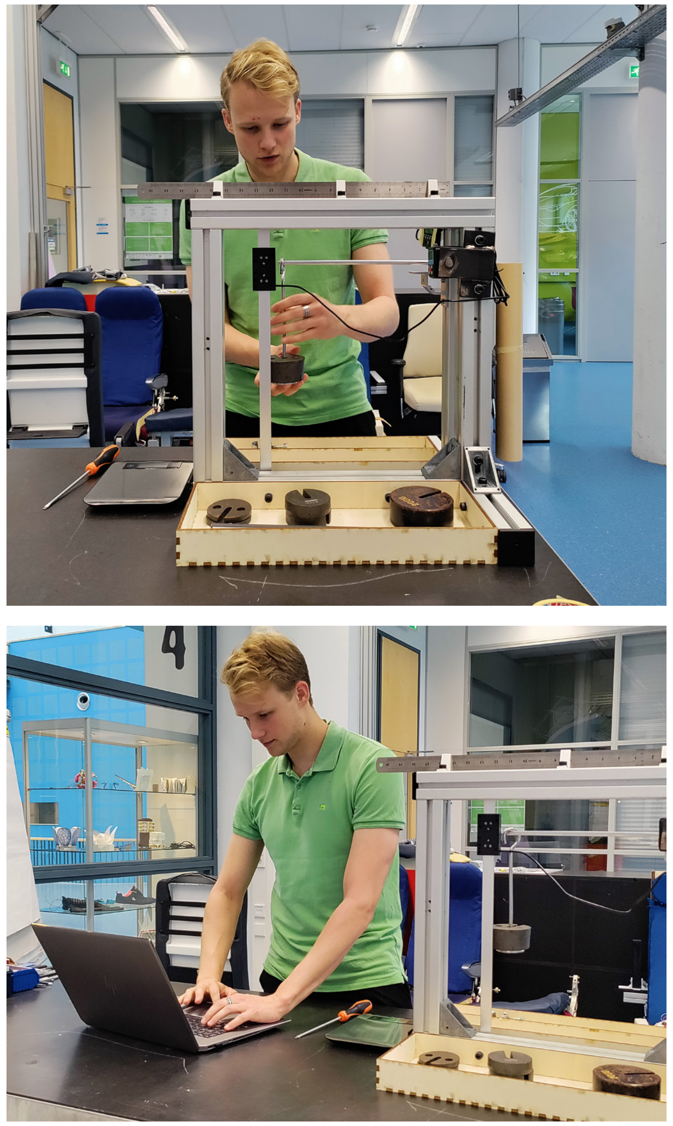


Figure 68: Participant executing usability test

The experiment generated qualitative data, being observings, verbal feedback and responses to open questions in the summary. It also generated some quantitative data, being the measurements that participants gather during the experiment and the ratings of ease of use they give in the questionnaire. First, the results from this test pass review, followed by a reflection on them. The full results are in Appendix 12.

10.2.1 Findings

Participants tended to favour thicker aluminium samples over thinner brass and steel profiles, relying on their intuition. Several issues with the torque sensor were noted, including frequent battery-saving shutdowns and initial confusion over its display and controls.

Additionally, the "zero" function of the digital ruler was not easily found, and some participants had difficulty determining the correct beam length for calculations.

The interaction with the digital ruler was challenging due to difficulties in positioning and reading, and participants found sliding it horizontally unintuitive. The ruler on top of the device was useful but too distant from the test sample, making precise measurements difficult.

Some participants found the assignment unclear regarding the role of the torque sensor, while others suggested labelling components for efficiency. In terms of ratings, participants rated sample fixing ease as 4/5, applying a load at 4.3, and measuring deflection lower, at 3.3.

Lastly, measurement errors in the first phase were higher compared to theoretical values but improved in the second phase, closer to the accuracy assessment.

10.2.2 Discussion

The user tests generate a lot of insight for improvement of the machine. Some of these insights have lead to improvements that are already implemented in the final Proof of Concept as presented in chapter 9. Due to time constraints not all improvements and considerations were incorporated in the final prototype. These potential improvements are mentioned in chapter 11.3 Recommendations.
First and foremost, measuring the horizontal position and the length of the sample is complicated and took too much guesswork. The same is true for the vertical position of the sample, which is important for correct deflection measurements. As suggested, a background with guiding lines improves this. This way, the digital ruler can also horizontally stay in the same place, which eliminates the issue that it is quite hard to slide sideways properly.
It is also important to minimise the slack around the grip as much as possible, as was also found during the accuracy assessment. This can also diminish the angling of the samples that sometimes occurs. Fortunately, the angling can also be compensated by adjusting the steel holder for the torque sensor, as it has slotted holes to enable slight position and angle adjustment. During the test, this turned out to help the accuracy of the measurements somewhat.
The participants indicate that the function of the torque sensor is unclear. In this experiment, this is understandable, as not much attention is paid to its added value. The focus here is solely on evaluating the interaction. In assessing the educational value, the torque sensor would play a more significant role. After explanation, participants understood this; for instance, one suggests that it could visually represent the relationship between force and distance, allowing users to experiment with it. Another suggests students could get blind weights of which they have to figure out the force they create, by using the torque reading and length of the beam.
Lastly, it is clear that the machine needs a clear accompanying manual or instruction sheet, combined with labelled components. This should give enough grip to start using the machine, but leave enough room for trial and error.
Despite the necessary improvements to the machine, the experiment does show that by having a hands-on experience with a subject like the bending of beams, the understanding of the relationship between all important factors comes automatically as they discover what they need to know and measure.

The evaluation could have generated more and better results with more participants. The choice to stick with one pilot and three user tests was also influenced by the period in which the tests were conducted, being the summer holiday. This meant the IDE faculty was relatively empty and specifically bachelor students were not present. In the next user test, which took place at the end of the project, participants from the actual target group are gathered.

10.3 User test: target group

This test is a final evaluation. The results of it can be a guide and base line for future developers of the EDA. The test involves the actual target group, first year UPE students that started their bachelor simultaneously with the final phase of this graduation project. The requirement that students must perceive the activity as enjoyable (R10) is also validated in this evaluation, as well as R19, dictating that users must be able to stand in an ergonomic posture when using the EDA. The observations can also lead to an initial indication if the durability requirement (R15) can be achieved.
In this test, the integration of the prototype in a workshop assignment is evaluated. This way both the concept and the educational module are tested. The target group test takes place after a few updates to the prototype that result from the usability test. There are also a number of aspects that have not yet been implemented, so these arise again during this study.
The evaluation method exists of a questionnaire that simultaneously functions as an assignment sheet with exercises as well as theory explanation. While the test is performed, observations are made. The full test plan is shown in Appendix 13.

The setup of this user test is designed to closely reflect real-world conditions, therefore it is conducted in a studio in the IDE faculty. The studios are commonly used for UPE workshops. The test also follows a structure similar to the UPE workshops, with an Ideation, Prototype and Evaluation phase. In Figure 69 is shown what the setup looks like.
The number of participants is six, performing the test in three pairs. The participants in each pair knew each other before the test, which is a deliberate choice in selecting them. This also resembles reality, as most students are grouped together based on their groups from the university introduction programme. Moreover, this is expected to make the participants more confident in performing the test, leading to clearer results.

To keep the instructions that students get consistent, the UPE staff chooses to use videos as instruction method between the Ideation and Prototype phase. With the same reason in mind, in this test the participants all get the same assignment sheet that includes the required theory. The researcher is however present to help with any questions and issues, just like real UPE workshops have a teacher or assistant present.

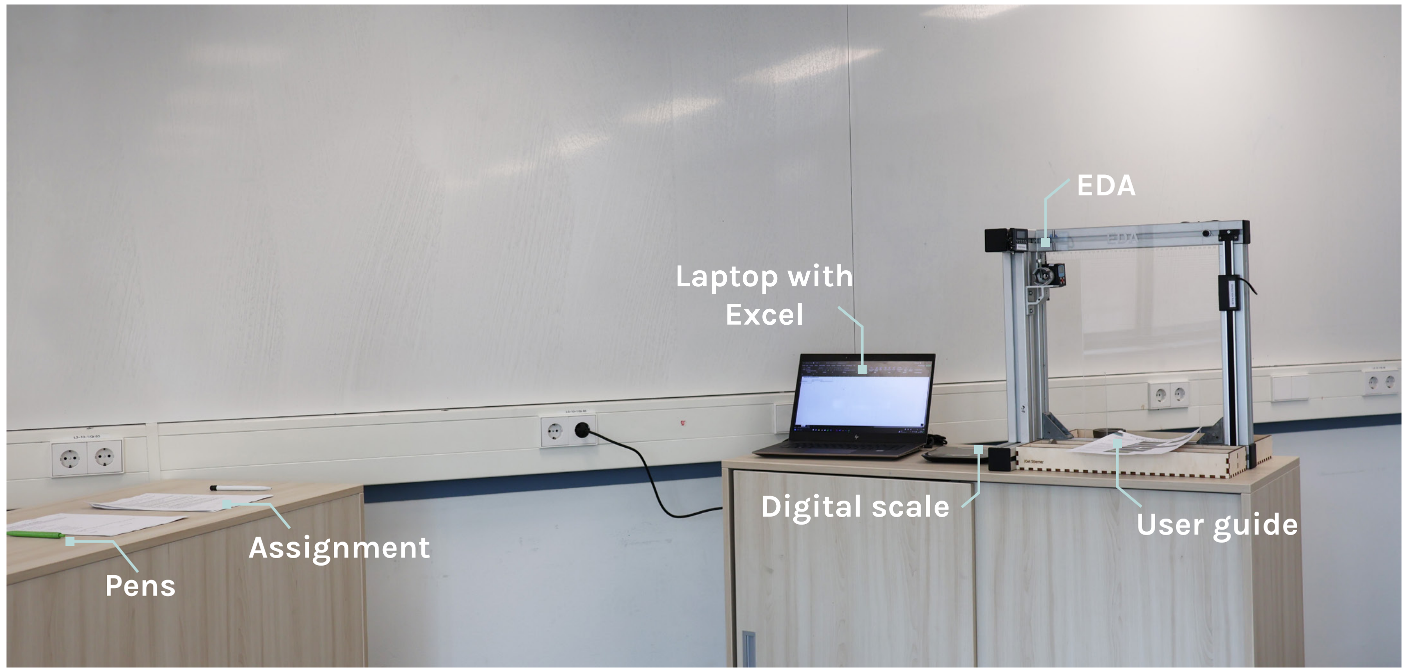


Figure 69: Setup of target group user test

In Figure 69 it is shown that the students have access to a laptop with Excel sheet, just like in the previous user test. This time, the sheet exists of two different tabs for the two different phases in the test (also shown in Appendix 13). In UPE workshops, the students mostly use Maple as software for calculations. This has been considered for the test, but Excel offered the opportunity to make a half-filled in framework for the students to work with and was therefore chosen. The main disadvantage, however, is the error-proneness of Excel sheets.

10.3.1 Findings

The results of the test are divided in the two methods of obtaining them, first the results from the observation and secondly the results from the assignment / questionnaires the participants filled in. Lastly, the results are discussed.

A picture of two participants performing the test is shown in Figure 70.

Figure 70: Two participants performing the test

Observation

During the 3 test rounds, observations were made on paper as well as video and photo recordings. The full results are presented in Appendix 13, the main findings from this part are as follows.

- The EDA and workshop are suitable as experiential setup with which scientific experimenting is possible
- The setup is well-suited for experimentation and allows students to make mistakes, through which they gain valuable insights, as is supposed to happen with PF
- Both practical improvements to the prototype are still necessary and more workshop-related, advanced enhancements that require further development, like how to get students to dare to experiment more
- Differences in character between participants clearly influence the way they approach the workshop and EDA. E.g. students who seem more confident started experimenting quicker than others
- The transparent guiding board helps to measure the height better, but it is not intuitive yet
- The digital ruler lacks a use cue indicating that it must be moved manually
- The slack in the grip-torque sensor connection makes measuring more complex and sometimes confusing
- One participant used the small grip as a tool to put the hanger on their (flexible sample) as shown in Figure 71.

Figure 71: Creativity in use of the accessories

Assignment and questionnaire

Each participant had their own sheet during the test, on which they had to write down answers to questions belonging to the workshop assignment. The last part of the sheet was an evaluation questionnaire. The relevant results from the first phase up until the theory explanation are as follows.

- All participants were first-year IDE bachelor students taking UPE for the first time, evenly split between female and male.
- One participant had studied one year of mechanical engineering previously, which influenced their understanding of deflection theory.
- Participants rated their confidence in solving statics and mechanics exercises at 2 or 3 out of 5.
- In the assignment, participants approached the task of selecting the best sample for an aeroplane seat's armrest similarly but in different orders.
    - The first and third pairs used a more structured and precise approach.
    - The second pair used a more trial-and-error method.
- Participants noted practical issues, like difficulties with the digital ruler, similar to what was observed.
- After reviewing beam deflection theory and the formula, most participants realised they had missed or provided incorrect answers in their initial responses (Figure 72).

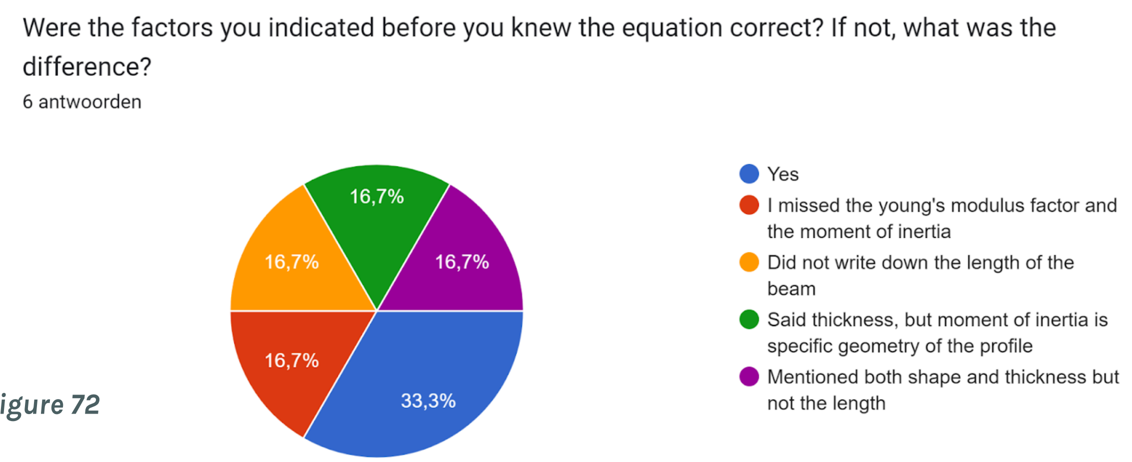


Figure 72

Participants began calculating, measuring, and comparing their results to theoretical values, indicating how well theory and reality corresponded. Some were unsure if their deviations were significant, reflecting their unfamiliarity with the material. The second group, which worked less systematically, had larger discrepancies, as shown in Table 9.

Table 9: Measurement results of second test round

Sample	Deflection - theory (mm)	Deflection - measured (mm)
PVC rod round	28.18	21
Aluminium rod rectangle horiz.	7.06	8.65
Aluminium tube round	4.01	31
Brass rod square	11.35	2.9
Steel rod round	16.91	49.31

Participants offered explanations for these deviations, citing general testing mistakes, measurement errors with the digital ruler, and potential inaccuracies in the provided Young's modulus and moment of inertia values. The third pair noticed that one sample bent less than the other in both theory and reality, which was correct.

In the evaluation, five out of six participants reported learning something new during the workshop, with only the participant who had prior mechanical engineering experience already familiar with the theory. Participants rated their enjoyment of using the EDA as 4/5, ease of use with two people as mostly 4/5, and confidence in what they learned as 3/5 or 4/5.

When comparing participants' confidence levels before and after the test, four out of six reported an increase in confidence, while two remained the same.

P1	P2	P3	P4	P5	P6
+1	+1	+1	0	0	+2

None of the participants experienced physical discomfort, and although none could perfectly recall the deflection formula without reference, five out of six remembered the correct variables, and four out of six had the correct structure.

Participants laughed at their final question about recalling the theory, leading them to review and reflect on how close or far their responses were to the correct answer.

10.3.2 Discussion

The workshop and EDA setup proved effective for facilitating scientific experimentation and promoting Productive Failure in students. One of the key observations was that the setup allowed students to make mistakes, thereby fostering learning opportunities that are core to the PF approach. However, there are areas for improvement, both in terms of the technical functionality of the prototype and the workshop experience itself.

When asked to rate how much they enjoyed using the experiential machine in the workshop, all participants rated it 4 out of 5. This good enjoyment score reflects a general sense of satisfaction and engagement with the experiential setup, despite the technical challenges and difficulties encountered along the way. Enjoyment is a critical factor in maintaining student motivation and engagement in learning, and this positive feedback suggests that the EDA is an effective tool for sustaining interest in complex topics like beam deflection. This leads to the conclusion that requirement R10 is achieved.

Related to motivation, it stood out that the second pair of participants seemed more confident and they dared to experiment more. Compared to the others, their results were less accurate, however this could be seen as "failing a lot, fast" which is actually beneficial for learning, according to the PF theory. If they actually learned more than the others cannot be concluded based on this test, however.

This aspect also brings up the realisation that they probably could have learned more if there was more time. The test duration was one hour, while a real workshop is around four. In this test, the participants also did not get an explanation for the errors in their results, or approval of the possible explanations they gave. Normally, they of course would get a solution.

Participants also reflected well on their performance, including explaining deviations between their calculations and measurements. In regard to their ability to recall the beam deflection formula: while none of them could remember the formula perfectly without reference, most had the correct variables or structure. This indicates that while their knowledge was not yet fully internalised, the workshop helped them establish a foundational understanding.

A number of technical challenges were observed during the workshop. For instance, the digital ruler lacked clear use cues, resulting in some confusion among participants. Similarly, the slack in the grip-torque sensor connection introduced additional complexity, making measurements less straightforward and at times inaccurate. These technical limitations may have contributed to measurement errors and the inconsistencies between theoretical and measured deflections. It is also possible that some material samples were slightly bent already prior to the test, as they have all been through accuracy assessment and the previous user test.
In terms of practical use, while the transparent guiding board was helpful in measuring height, it was noted that its operation was not entirely intuitive. These issues highlight the need for further refinement of the tools and equipment to enhance usability and reduce the cognitive load on participants, allowing them to focus more on the conceptual aspects of the workshop.

Overall, the results of this target group user test are a good benchmark for the current state of the project, which will be valuable for further development.

11 Conclusion

In this chapter, the design goal and the project's result and value are reviewed. A reflection on the requirements is performed and recommendations for the future are discussed.

The original assignment was to:

*Create an **experiential machine** to improve the **hands-on** education in **basic engineering principles** for first year bachelor students*

This subsequently evolved into the following after initial exploration of the problem space:

*Create an experiential machine that can serve as an **educational tool** to teach **statics** in a hands-on way with a focus on **beam deflection***

With the Educational Deflection Analyser, the goal of providing a hands-on experience with one of the UPE subjects has been reached. Some, but not all design requirements are fully met, which is discussed in 11.2. First, in-depth conclusions are drawn about the added value of the design. This is done using the DVF framework (desirability, viability, and feasibility) ("IDEO Design Thinking," n.d.). This way can be considered if the EDA will be a succesful product, as all three elements play an important role in this.

11.1 Value

The value that the EDA adds to engineering education is determined by using the question: is the EDA desirable, feasible and viable?

11.1.1 Desirability

In this thesis report is analysed what the target group needs to get a good understanding of basic engineering principles in a changing educational context. With the simplification of engineering education, the same subjects need to be taught in shorter time. After analysis of the different UPE subjects, statics and beam deflection are found to be relevant but difficult subjects for design engineering students. The EDA therefore plays a role in making this subject enjoyable, stimulate deeper learning and improve retention of conceptual knowledge (with Productive Failure).

The EDA's effectiveness has been evaluated in a usability test and a target group user test with a focus on workshop integration. The results show the EDA can be effective in teaching students about beam deflection theory and participants rate the experience well on enjoyment. Most students' confidence improves as well, although conclusions about significance cannot be drawn at this stage.

This would ultimately require a comparative evaluation of the EDA experience with the traditional approach. Simultaneously, the UPE coordinators deploy Productive Failure and Experiential Learning Theory because they are convinced this is an effective approach, based on their previous experience and research. The EDA fits this approach and it can therefore be stated that it is desirable.

Nevertheless, there are some issues with the usability. An example of this is measuring the deflection, which has been improved with the transparent guiding board, but still turned out to be a finicky process in the last user test. It cannot be denied that these issues need attention, would the EDA be deployed in UPE in the future.

11.1.2 Feasibility

As mentioned earlier, the design has been tested with the target users—first-year students. These tests demonstrated that students can successfully perform beam deflection measurements with the EDA, provided they are given a basic user guide during the workshop. Participants were able to grasp the essential functions quickly, and many of the more detailed aspects were intuitively figured out through hands-on experience.

The EDA has been purposefully constructed using readily available, off-the-shelf components to ensure that the production process is both cost-effective and scalable. By minimising the number of custom-manufactured parts and limiting the amount of manual machining required, the overall complexity of building multiple devices is kept low. This makes it feasible to produce the EDA in larger quantities. Additionally, the use of common materials and components ensures ease of maintenance and repair, contributing to the long-term feasibility of the device.

Future iterations could further enhance feasibility by exploring automated assembly methods, reducing production costs while maintaining functionality.

11.1.3 Viability

The costs of one individual EDA are €290 and is within budget. It is important to note that this is an indication for the current prototype, which needs to undergo iteration before use in UPE. The price can also be lower if the machines are made in larger batches.

Maintenance on the EDA can be done with standard tools and comes down to replacing batteries and samples that have been bent too much. Parts that are prone to breaking are mainly the storage compartments that are made from plywood. This could easily be overcome if they would be made from acrylic or another more durable material.

From a sustainability perspective, the EDA has a relatively small environmental footprint. The primary materials that may require disposal are broken samples and batteries. However, as the samples are made from pure materials, they can be easily recycled. In future iterations, such as those incorporating Arduino integration, the sensors could be powered directly by the microcontroller. This in turn would be connected to the mains, reducing reliance on disposable batteries.

11.2 Reflection on requirements

The majority of the requirements (indicated with R+number) have been met and can be found in Table 10. However, there is also an amount that is still in progress of achievement. This is due to the time constraints of the project which means some parts of the prototype are prioritised in evaluation or implementation over others. Some of these limitations will be discussed next.

First of all, first year bachelor students acquire a better understanding of statics and/or beam deflection with this design, has not been entirely validated. This is not one of the design requirements, but a given criteria from the design brief. This should definitely be one of the first things to test in future development.

Besides this, the idea behind a workshop with an experiential machine following the PF approach (R1) is also to improve retention of conceptual knowledge (R6). The EDA is a promising start to achieve this and positive feedback from initial user tests indicates there is potential to expand and improve the design, followed by full evaluation. In this evaluation, a reversed approach (stress and strain before statics) could even be tested.

The accuracy of measurements with the EDA compared to calculations with the common deflection formulas is not consistently below an error of 30% (R14). There are multiple explanations for this, of which one at least is certain; this is the way of measuring is not ideal currently and should be improved. Other than that, it is e.g. hard to determine what Young's modulus values exactly should be used, therefore the accuracy is not only influenced by the design of the EDA.

If the EDA can withstand intensive use by inexperienced students for two weeks per year for 5 years before maintenance (R17), is hard to say. However, the design has been used by the target group during final user tests. This showed that the general structure is very durable, but some weak points are observed. The wooden, laser cut storage compartments are slightly vulnerable, especially noticeable when users let the weights slide of a sample or drop them on the wood. The material samples will also undergo material fatigue after many tests, especially when students might bend them past their yield strength.

The dimensions are appropriate for the EDA to fit on a standard size desk in the IDE studios (R20). It is however heavier than the maximum of 10 kilograms as per requirement R19 and in future development this should be decreased. The easiest part to cut weight from is the frame profiles.

During final user tests, participants were asked if they physically noticed discomfort. None of the participants indicated any discomfort, like heavy loads on their body or limbs. Nevertheless, extensive testing could be performed in future development to validate if the requirement for an ergonomic standing posture for users is met (R21).

The manufacturing of one EDA should be under 4 hours, starting from unprocessed parts like uncut aluminium extrusions (R22). This requirement does not have a detailed foundation, but quick calculations show that this is probably manageable in three hours. It is also clear that if one were to manufacture 20 EDA's, the time per machine is lower, resulting in a more efficient manufacturing process. This should be taken into account in future development.

Safety wise, the EDA does not use any custom electronics at this stage (R23). This also means the electronics that are used are CE certified and have their own protection. The machine does contain parts where objects need to be clamped by means of a bolt. Technically, fingers could get stuck here (R24) - the odds are however very low, as long as the EDA is used with minimum common sense and caution.

In the following overview in Table 10 is shown which requirement is met and which is still in progress of achievement, or not achieved at all.

Table 10: Program of requirements including status

	Requirement	Status
R1	The design and assignment module must enable the Productive Failure approach	Achieved
R2	Must offer a physical, hands-on experience in statics and beam bending	Achieved
R3	Must be scalable to 20 units	Achieved
R4	Cost must stay under €500	Achieved
R5	The design and assignment must be structured so that they can be fully used and completed within a 4-hour afternoon workshop	Achieved
R6	Must improve the retention time of students over a traditional approach	In progress
R7	The assignment module needs to follow the structure as suggested in the Productive Failure Design Cycle	Achieved
R8	The design must be accessible to at least two persons at the same time	Achieved
R9	The design must require students to manually set up an experiment with the machine (no plug-and-play)	Achieved
R10	The design must incorporate elements that enhance students' intrinsic motivation ("wantivation") by ensuring that they perceive the activity as enjoyable and interesting	Achieved
R11	Load application must be possible in steps of 1 N	Achieved
R12	The design must provide a way of visualising the reaction moment in cantilever beam supports	Achieved
R13	The design must provide a way of measuring beam deflection with a resolution of 1 mm	Achieved
R14	The maximum relative error between expected and measured deflection values must be 30%	Not achieved
R15	The design must allow users to fix different materials	Achieved
R16	The design must allow users to fix different profiles	Achieved
R17	Must withstand intensive use for two weeks per year by inexperienced students, at least 5 years before maintenance is required	In progress
R18	Maintenance must be possible with standard tools	Achieved
R19	Must not weigh more than 10 kg to make transport in the faculty possible	In progress
R20	Must fit on a standard desk in an IDE studio	Achieved
R21	The dimensions must be so that the user can stand in an ergonomic posture while using the design	Achieved
R22	Must be manufacturable in under 4 hours, starting from unprocessed parts	In progress
R23	Electronics with open contacts must be shielded for safety	Achieved
R24	The risk of fingers getting stuck or pinched must be mitigated	Achieved

11.3 Recommendations

As described before, there are certain aspects of the EDA and the workshop that need to be evaluated more. Simultaneously there are also already clear improvements that the design would benefit from. In this section, suggestions for all these cases are given.

11.3.1 Evaluation

First of all, to test the effectiveness of the EDA, a long-term vision is required. The goal of improving the engineering education is for students to use the obtained knowledge and skills more and better than they do currently and to enjoy doing so. Proving if experiential machines like the EDA contribute to this, can be tested in the future. A suggestion could be to perform an A/B test with one group that first uses the EDA and are then taught about statics and beam bending. At the same time the other group gets the traditional approach, being the current order of teaching UPE subjects without experiential machines. Furthermore, the coordinators of the course will keep researching the retention of UPE knowledge in students over the coming years.
It is important to consider ethical limitations when testing educational approaches on students, especially when one group could be disadvantaged compared to the other.

11.3.2 Design improvements

A few practical improvements are discussed, followed by recommendations for expanding the design.

- The connections between the frame, torque sensor and grip should be improved with a specific focus on tolerances, to minimise slack.
- A guiding bar to help the user see what the real neutral position of the beam sample is (black bar in Figure 73). This is recommended after accuracy tests showed that there is a little bit of play in the connection between the grip, the sensor and the frame.

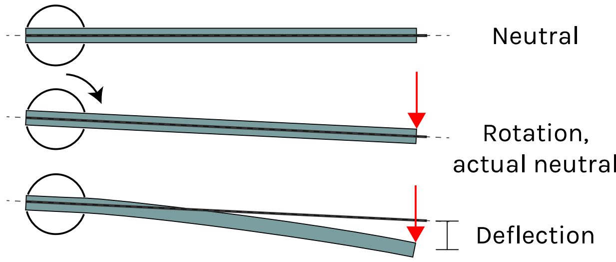


Figure 73: Guiding bar addition

The thin black bar turns with the beam when the load is applied on the sample, but does not bend.

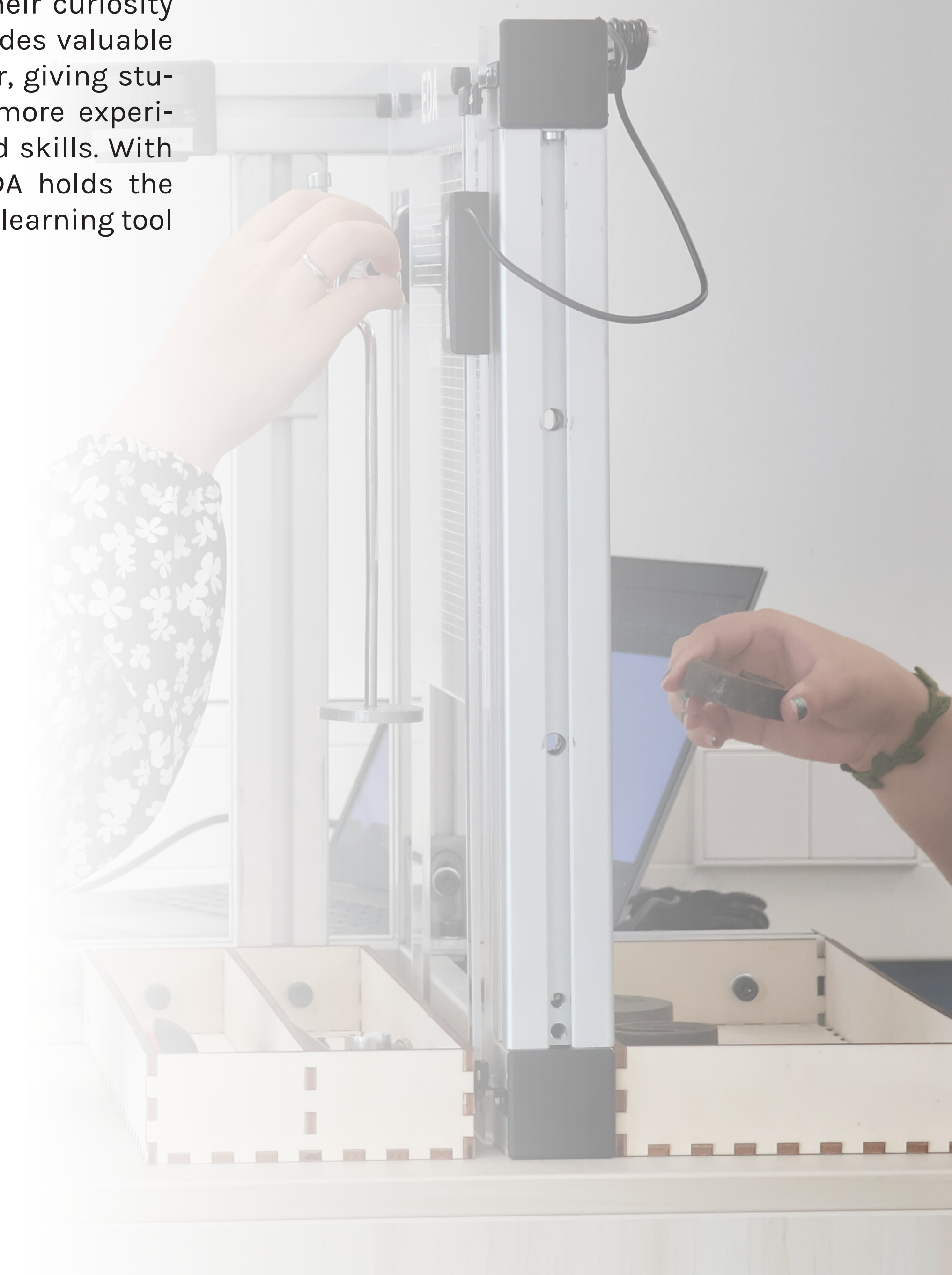
- The workshop should incorporate the concept of torque and counter moments more.
- The design should be at least 3 kilograms lighter.

Design iterations could include:

- Improving the looks of the EDA, including making sure the grip looks more like a typical 'fully fixed support' as in statics theory;
- Precise, mechanic load application methods like an electromotor with winch or linear actuator;
- Continuous deflection measurements;
- Arduino integration, meaning load aplication and deflection measurements could be performed automatically;
- Arduino integration with the torque sensor;
- Graphical user interface on laptop like the LETT for easy control, measurements and implementing digital data collection.

11.4 Final word

The current development of the EDA demonstrates promising results, however the effectiveness of the EDA is yet to be fully evaluated. Several areas for improvement have been identified, which provides exciting opportunities for further enhancement. A group from the master's course Products Now will build on these results for deeper evaluation and redesign.
For now, the proof-of-concept EDA is a partially functional prototype with the potential to engage students by sparking their curiosity to learn something new. It provides valuable insights into material behaviour, giving students a design advantage, as more experience typically leads to enhanced skills. With continued development, the EDA holds the potential to become an effective learning tool in the future.



11.5 Design evolution

As described in the introduction, this project has followed a Triple Diamond pattern. In Figure 74 can be seen how the design of the EDA evolved through three phases from simple sketches to a functional prototype.

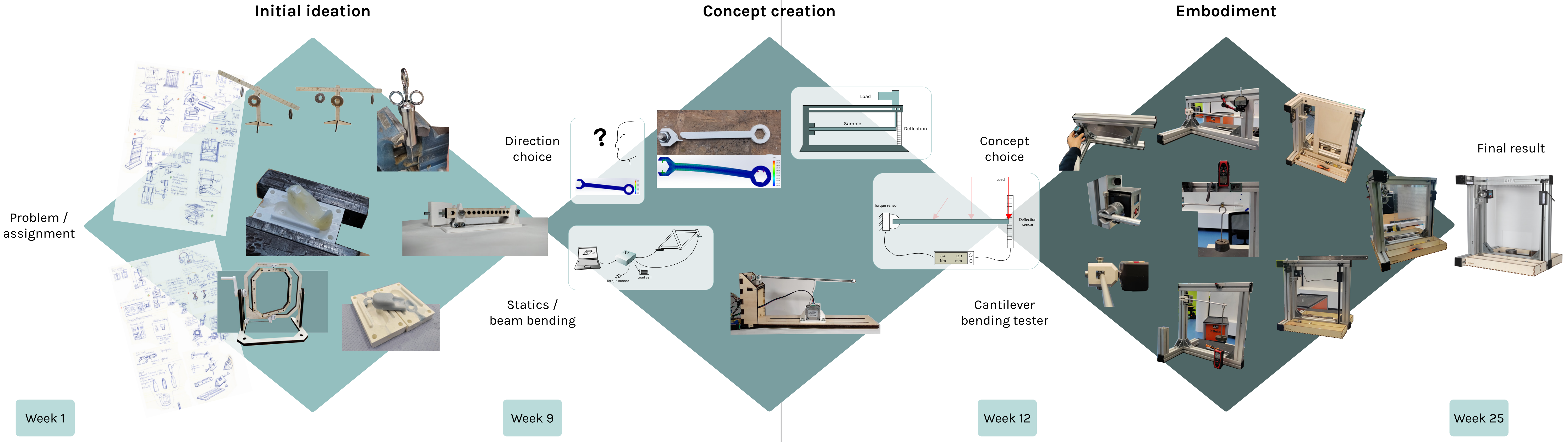


Figure 74: Design evolution

Acknowledgments

There are a few people that have made this project possible that I would like to thank.

12

First of all my supervisory team, Wilfred van der Vegte (chair) and Stefan Persaud (mentor). Without Wilfred's critical vision on the project, it would not have been the level it is right now. I also want to acknowledge his responsiveness. Furthermore, I want to appreciate Stefan's inspiring vision and mission about education and lastly the motivational boosts he gave me at the right moments.

I would also like to thank Robin, with whom I first took the statics course during our first year of the bachelor's programme. Now, as we complete our master's degrees, it feels fitting that we once again find ourselves working on a project centred around an engineering course. I appreciate the start we made together in this project, conducting a questionnaire and performing some initial analysis.

Next, I am grateful for the assistance I got from the PMB employees and specifically Wiebe. He brainstormed with me and together we designed the grip for the EDA. Besides this, he helped me with laser cutting and saved me a lot of time by recommending an online tool for laser cut boxes.

I would like to thank the Applied Labs for giving me a place to work and store the EDA. Martin and Adrie have both helped me greatly with the project.

Lastly, I am thankful for the people around me, my family and friends, who have continuously motivated and supported me throughout this final chapter of my education.

In Appendix 15, a personal reflection on this graduation project is included. With this, I would like to conclude the main part of this report and sincerely thank the reader for taking the time to read through it.

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Appendices

Appendix A. Original assignment

Design Manufacturing Machines for Education

Do you like making stuff yourself where you would normally need machines in a factory?
Are you interested in designing manufacturing experiences for IDE students?
If YES than we are looking for you: an enthusiastic maker to develop applicable test-setups which can be used to enhance learning in our engineering bachelor courses.

An example of a possible experiential machine to learn about injection molding [Gibbon, 2022] & FormBox: Vacuum Former

Within the first-year engineering course "Understanding Product Engineering," students are introduced to the fundamentals of mechanics of materials and unfortunately primarily limited to theoretical aspects, and there is a need for a more hands-on understanding of the basic principles.

Currently we have one experiential setup, the LETT (a simplified tensile tester machine), where students get hands-on experience on material properties such as Young's modulus and yield strength. However, there is a lack of diversity in experiential setups, particularly those related to manufacturing techniques, product architecture, and statics. The desire is to broaden the students' practical exposure beyond the existing setup.

We want to improve (y)our education by developing additional experiential machines and workshop materials aligned with our Productive Failure approach. Specifically, we are seeking a student who can work on machines related to manufacturing techniques (e.g., injection molding), product architecture (e.g., different fastener techniques), and statics (e.g., bending of beams).

Coaches: Bas Flipsen and Stefan Persaud ☺

upe-io@tudelft.nl

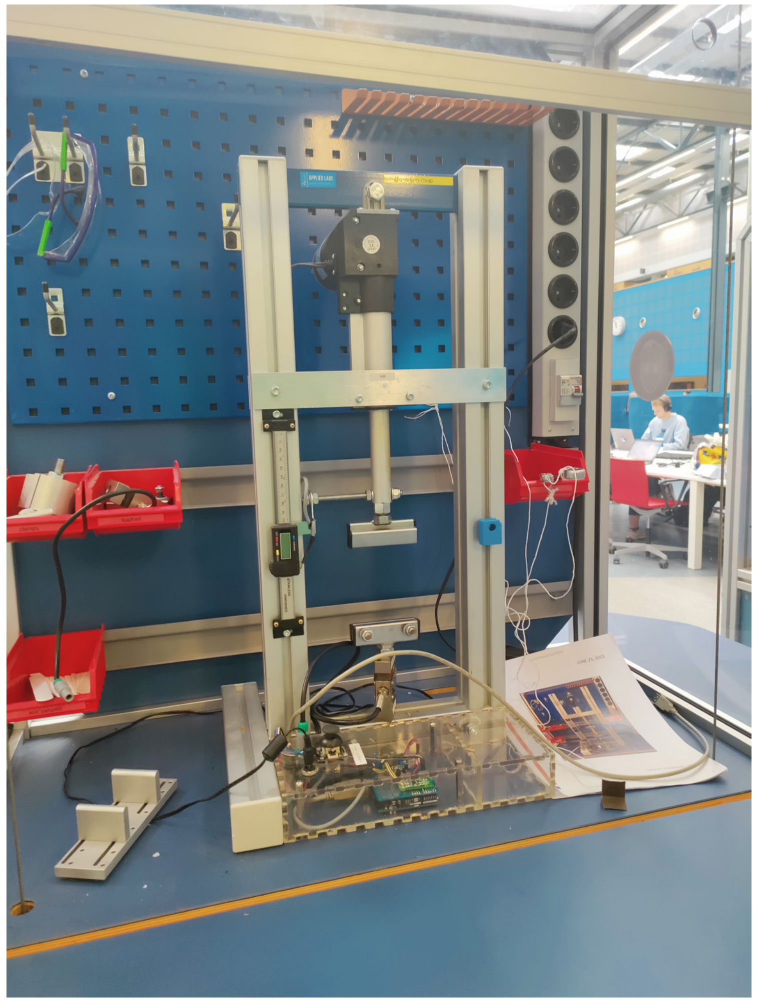
Contact Bas Flipsen or Stefan Persaud for more details on how you can contribute to enhancing our educational and furthering the Productive Failure approach in our course.

IPD GRADUATION PROJECT

Appendix B. Design Brief

Project title: Designing experiential machines for engineering education

Introduction:
Within the first-year engineering course “Understanding Product Engineering”, students are introduced to the fundamentals of mechanics of materials. The course consists of 8 weeks with each their own topic, ranging from basic statics and material properties to manufacturing and fastener techniques. There is one experiential setup, the LETT (a simplified tensile tester machine) (see Figure 1), where students get hands-on experience on material properties such as Young’s modulus and yield strength. The first year consists of 350 students and during this course they usually have an afternoon to use such a machine to get practical experience with the current week’s topic.
The course teachers Bas Flipsen and Stefan Persaud apply the Productive Failure approach, meaning that students are encouraged to try principles and methods out by themselves, during which things are allowed to go wrong. It is stimulated to learn from mistakes. In the old bachelor curriculum, this course was still split up into multiple separate courses like Statics, Design for Manufacturing and Engineering for Design. They involved, amongst others, building a friction coefficient measuring device with the help of Arduino electronics and analysing the material properties of a chosen product. The engineering courses are now significantly more concentrated and every subject has to be taught in way shorter time.
The elective Materials & Manufacturing and the minor programme Advanced Prototyping also involve knowledge and skills about these basic engineering principles and their coordinators Sepideh Ghodrat and Willemijn Elkhuizen are therefore also stakeholders.

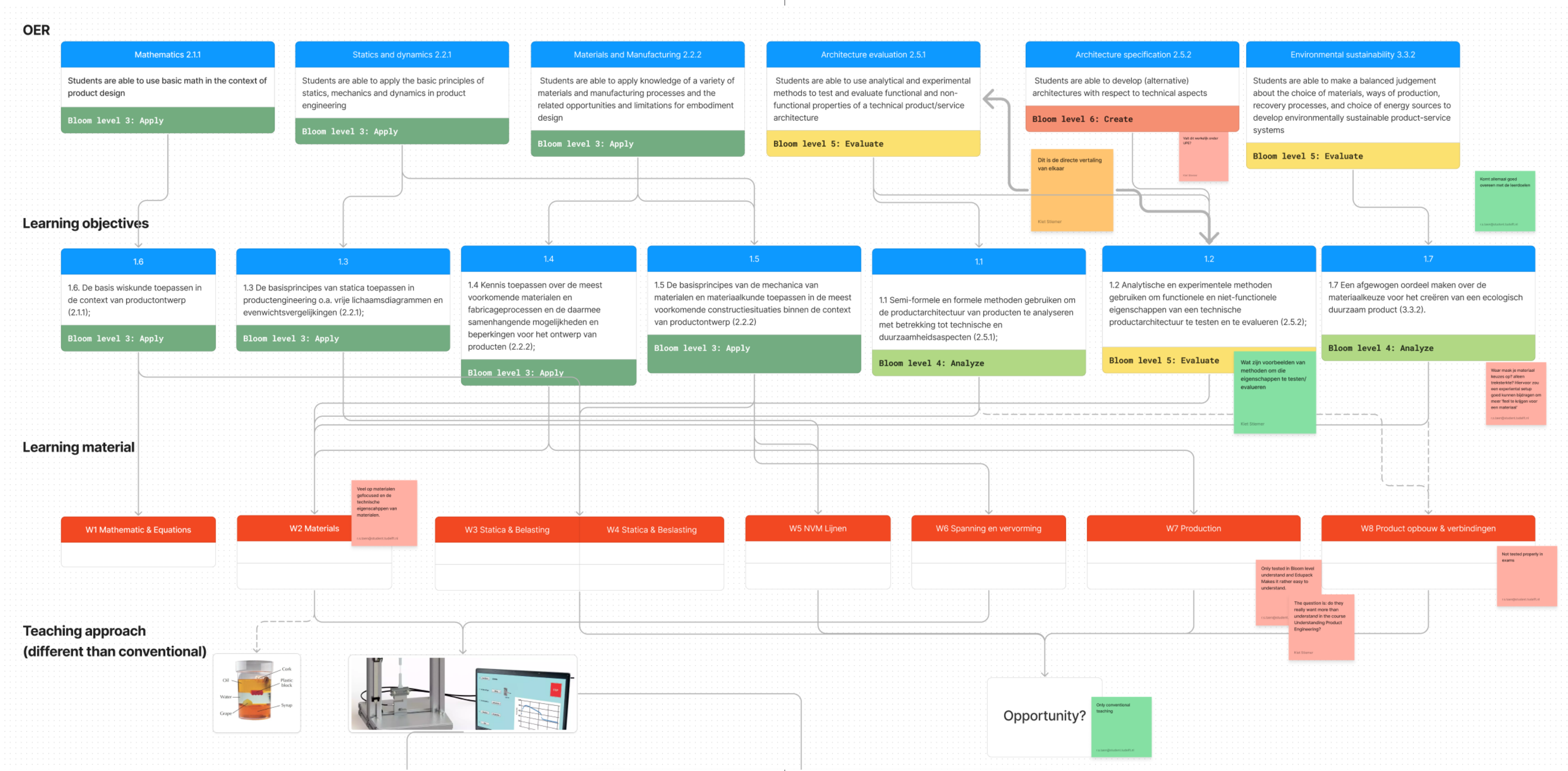


Problem Definition:
There is a lack of (diversity in) experiential setups, particularly those related to manufacturing techniques, product architecture and statics. It is of great value that students can learn about these techniques in a hands-on way, as this stimulates the learning process. Especially the more abstract principles like statics are easier to understand when put into practice. The course and its coordinators want to develop the Productive Failure approach, in which these experiential machines play a big role.
Students can stare at a text book for hours and get a vague understanding, or spend one afternoon practising this theory and understand it way better. This will create value later in their studies or career, as however you slice it, they will encounter moments where their knowledge about basic principles helps them. Furthermore, engineering should be fun and attractive to beginning design engineers. It is often seen as difficult and they get demotivated quickly. The imagined experiential machines should spark more enthusiasm for the engineering side of IDE.
These machines can also be deployed in the mentioned elective and minor, as it might create a low entry level opportunity to test or create a quick prototype.

Assignment:
Create an experiential machine to improve the hands-on education in basic engineering principles for first year bachelor students.
To complete this assignment, I will diverge and converge three times. First, some literature research and interviews or questionnaires need to be carried out to find out the hurdles that first year students experience and resulting potential knowledge gaps (diverge). This research leads to a fitting set of requirements and relevant directions (converge). Then for the relevant UPE subjects, a lot of different simple, potential setups will be ideated (diverge). After prototyping the relevant ones and evaluating them during tests, one needs to be chosen (converge), which will be around the mid-term. This idea will be iterated again (diverge) and then tested with representative participants. This leads to a final design which will be a full functioning machine (converge).

Motivation and personal ambitions:
Between my bachelor and master I studied mechanical engineering for a year. After, I started IPD during which I worked on an AED project that was leaning heavily towards mechanical engineering. Following up I became an intern at the same company, KUBO Greenhouses, and built a full size prototype of the AED machine on my own.
This graduation project really spoke to me as it is about the technical side of industrial design, which is clearly in my lane. The project also involves making physical, mechanical prototypes. This is a skill I have developed over the years which I hope to prove and of course improve.
Knowledge and skill I do not possess elaborately yet, but that I would like to have, is about didactics. I personally love to teach people about things I am passionate about. I have been told I am naturally quite good at it, but I would like to know more about teaching principles and methods like the Productive Failure approach.

Appendix C. Design opportunity analysis

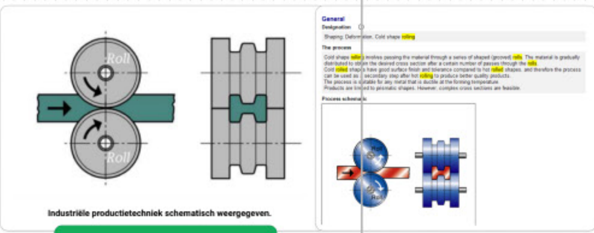


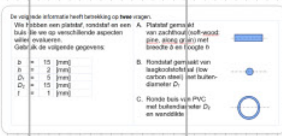
Exam questions

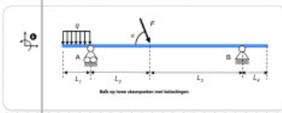
Tentamen 22/23

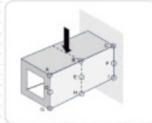
Nr.	Onderwerp	Bloom level
2	Materiaal (kunststof codes)	Bloom level 2: understand
10	Milieuvriendelijkheid / materiaal	Bloom level 3: apply
3	Statica (VLS herkenning)	Bloom level 2: understand
5	Reactiekrachten /momenten	Bloom level 3: apply
7	Statica + NVM lijnen	Bloom level 3: apply
8	Spanning + NVM lijnen	Bloom lvl 4: analyze
4	Vervorming	Bloom lvl 4: analyze
9	Spanning en vervorming (en heel klein beetje verbindingen)	Bloom lvl 4: analyze
1	Productie	Bloom level 2: understand
6	Productopbouw (maattekeningen)	Bloom level 2: understand

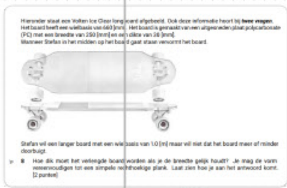
Meer op level 2 dan de her-23/24

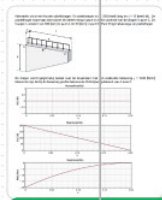












Tentamen 23/24

Nr.	Onderwerp	Bloom level
1	Productie	Bloom level 2: understand
2	Materials, Spanning en vervorming	Bloom lvl 4: analyze
3	Vervorming	Bloom lvl 4: analyze
4	Statica	Bloom level 3: apply
5	Spanning + NVM lijnen	Bloom level 2: understand
6	Spanning + NVM lijnen	Bloom level 2: understand
7	Spanning	Bloom level 2: understand
8	Statica & Belasting + vervorming	Bloom lvl 4: analyze
9	Statica & Belasting + vervorming	Bloom lvl 4: analyze
10	NVM lijnen	Bloom level 2: understand
11	Materials	Bloom level 2: understand

Hertentamen 23/24

Nr.	Onderwerp	Bloom level
9	Milieuvriendelijkheid	Bloom lvl 5: evaluate
7	Materiaaldeterminatie	Bloom lvl 4: analyze
2	Statica	Bloom level 3: apply
4	Reactiekrachten/ momenten	Bloom level 3: apply
5	NVM lijnen	Bloom level 3: apply
3	Buiging	Bloom lvl 4: analyze
6	Vervorming en materialen	Bloom lvl 4: analyze
8	Trekbelasting	Bloom lvl 4: analyze
10	Spanning	Bloom lvl 4: analyze
1	Productie	Bloom level 2: understand

Alleen op bloom level 2, understand getest

Opportunity?
Nog geen experiental learning

Opportunity?
Nog geen experiental learning

Opportunity; hands on feel for materials and manufacturing processes and their oppertunities and limitations for embodiment design.

Opportunity?
Nog geen experiental learning

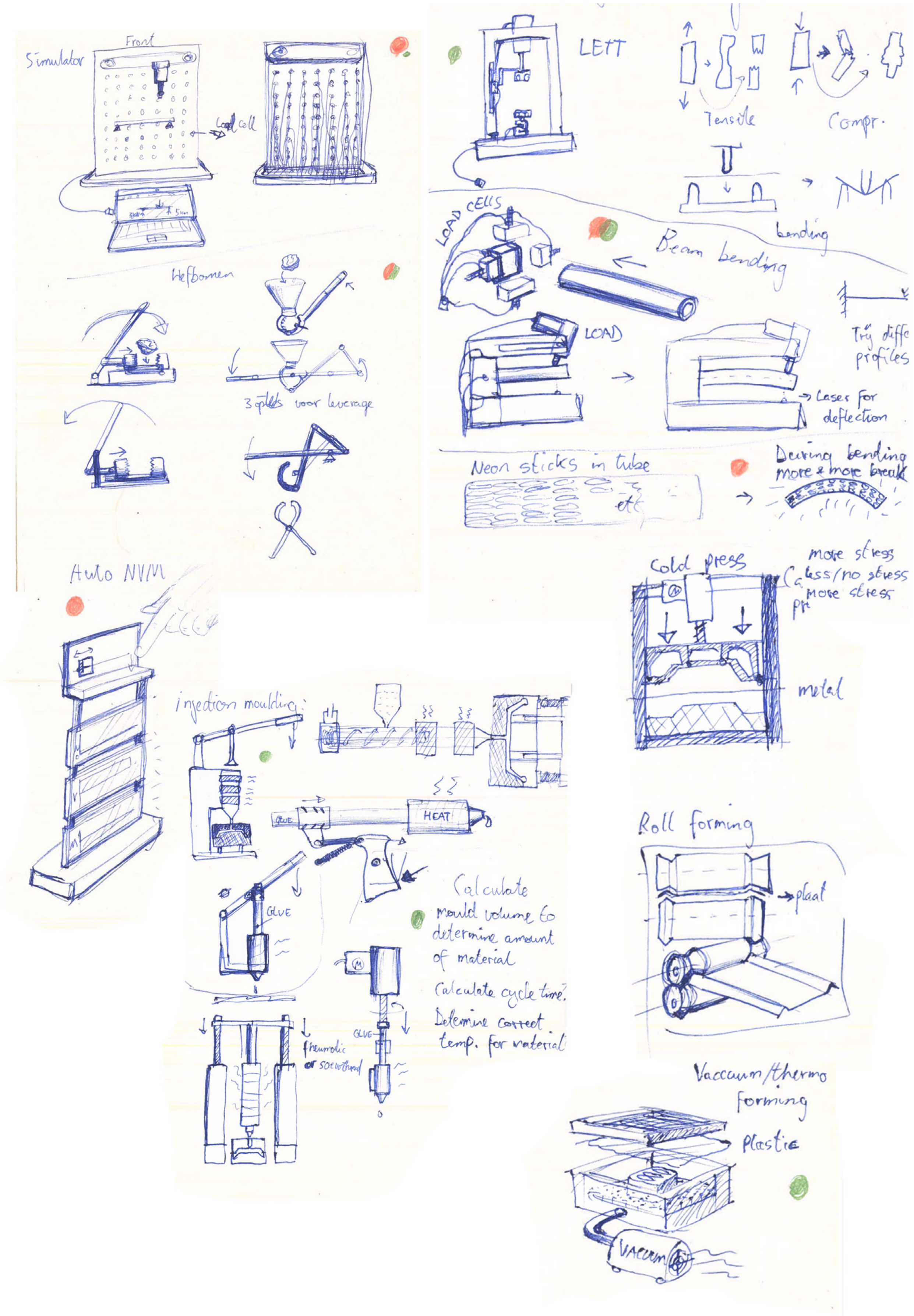
Opportunity?
Maar wordt weinig getoetst, werkelijk relevant?

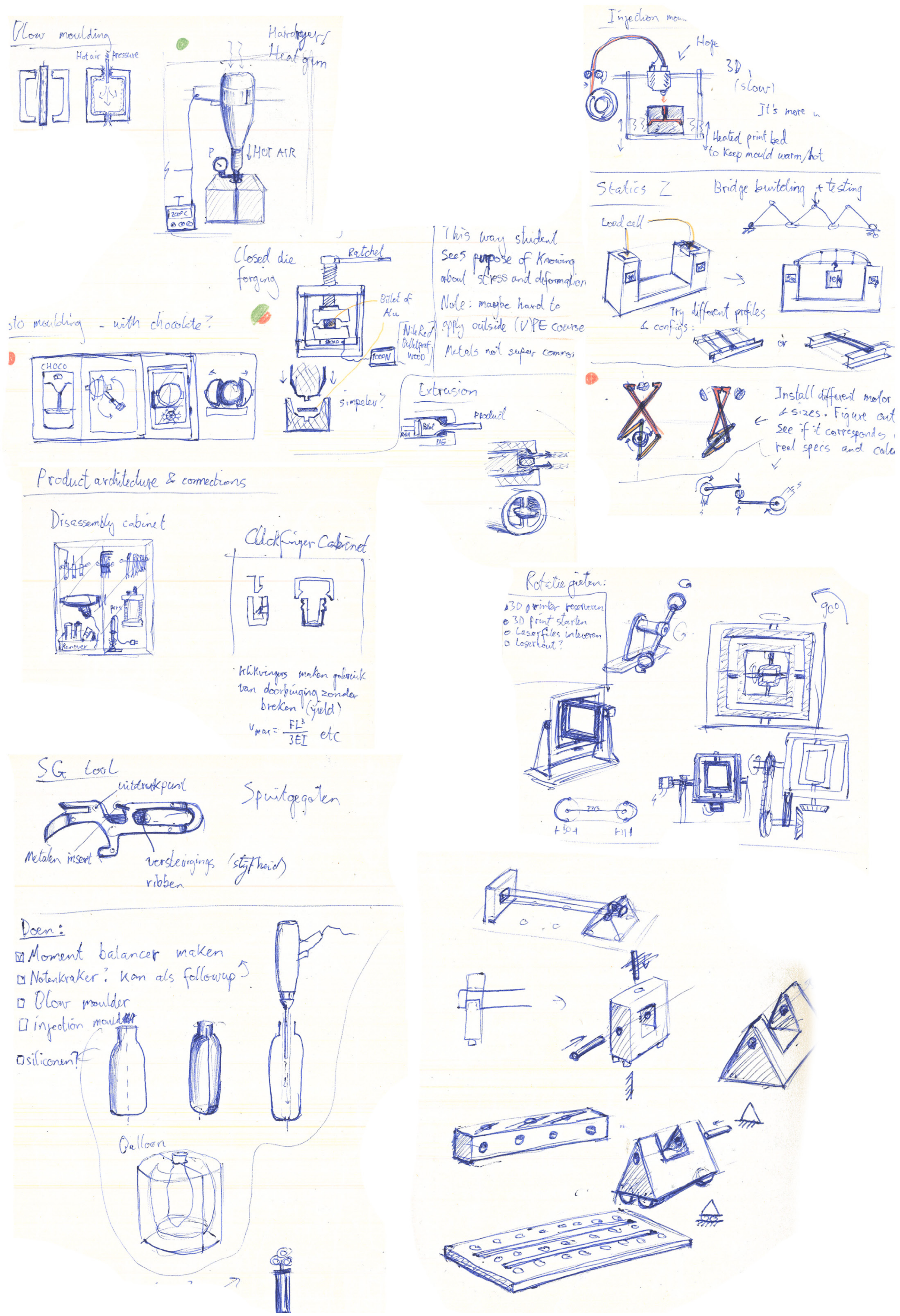
Dit kunnen we even vragen

Kiet Stiemer

Appendix D. First ideation

In a few weeks, a lot of ideas were generated for the different UPE subjects. In the following pictures, the majority of the created sketches is shown in a collage.



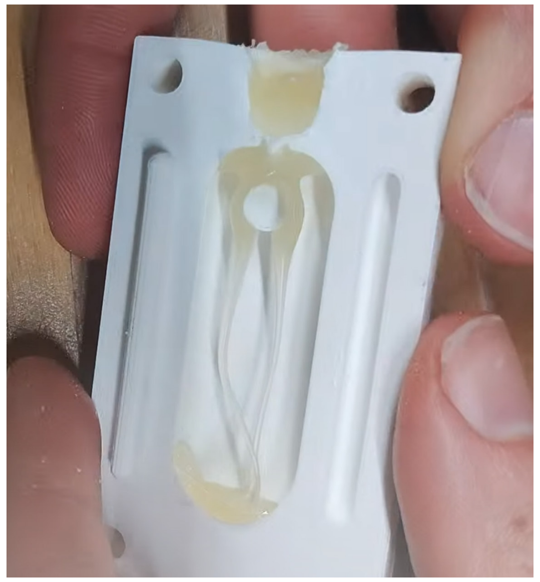


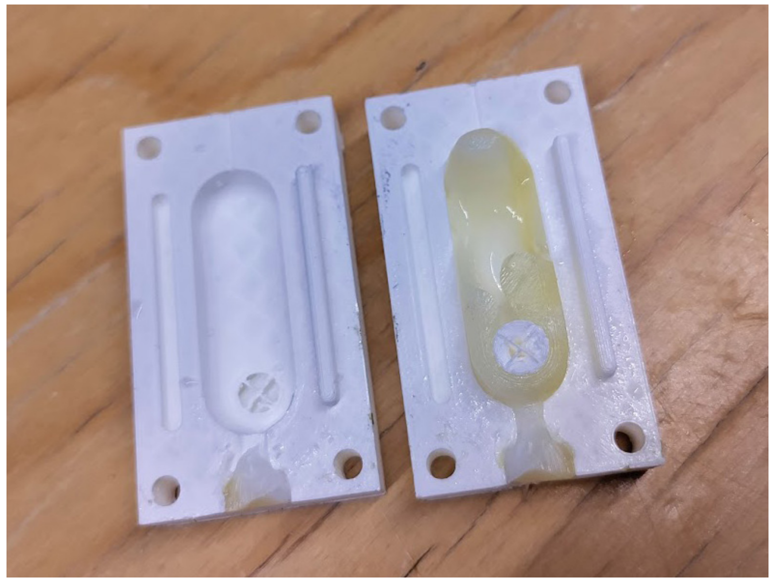
The following ideas were also made into prototypes:

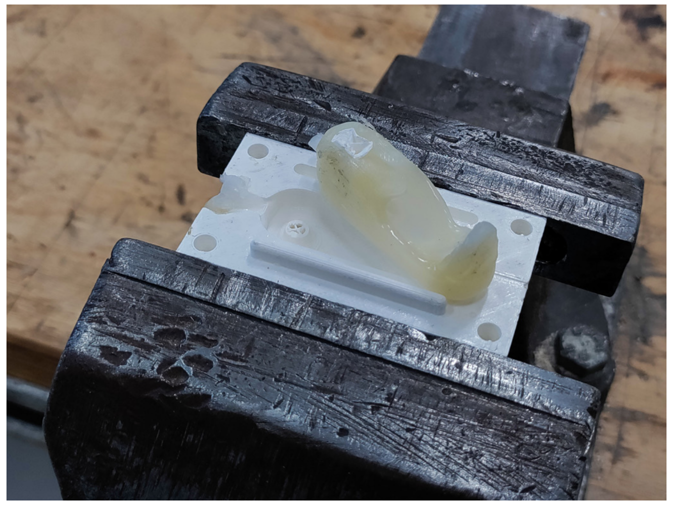
- Moment balancer

This tool is simple in nature and explains the principle of a ‘moment’. It allows the user to place weights on set distances. A moment is a force acting over a distance, calculated with $M = F*d$. This way you can balance out the arm, for example by placing one weight on 8 and two weights on 4. This is the same principle as an old fashioned scale.
The tool could also be used to make students ‘feel’ the moment, by letting them hold the arm in the centre and having someone else put weight on the arm. They will feel the force on their hand increasing and the arm trying to turn around the axis. They are delivering the ‘counter moment’, which could be related to the counter moment in statics theory.
This setup is quite simple and as is only explains one concept, not allowing for a lot of experimentation. It would probably be most suitable as a showcase in a lecture to explain moments.

- Glue injection moulding

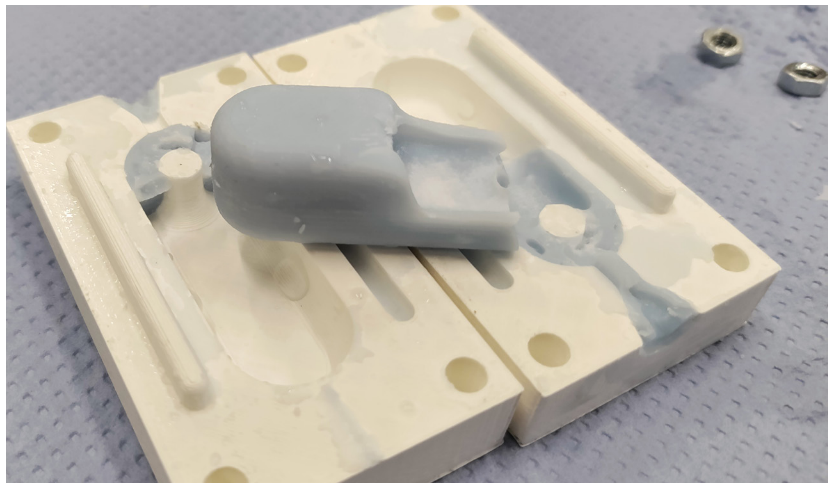
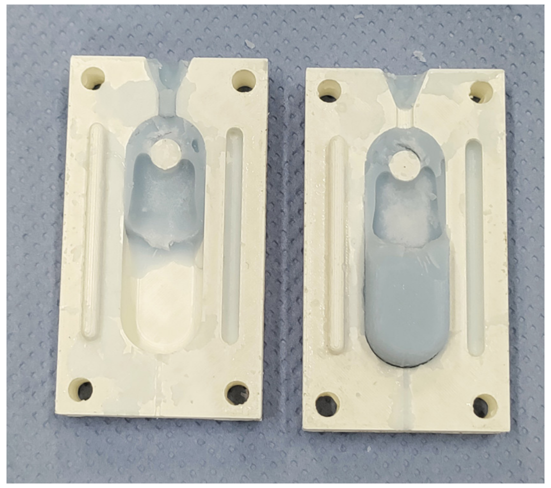






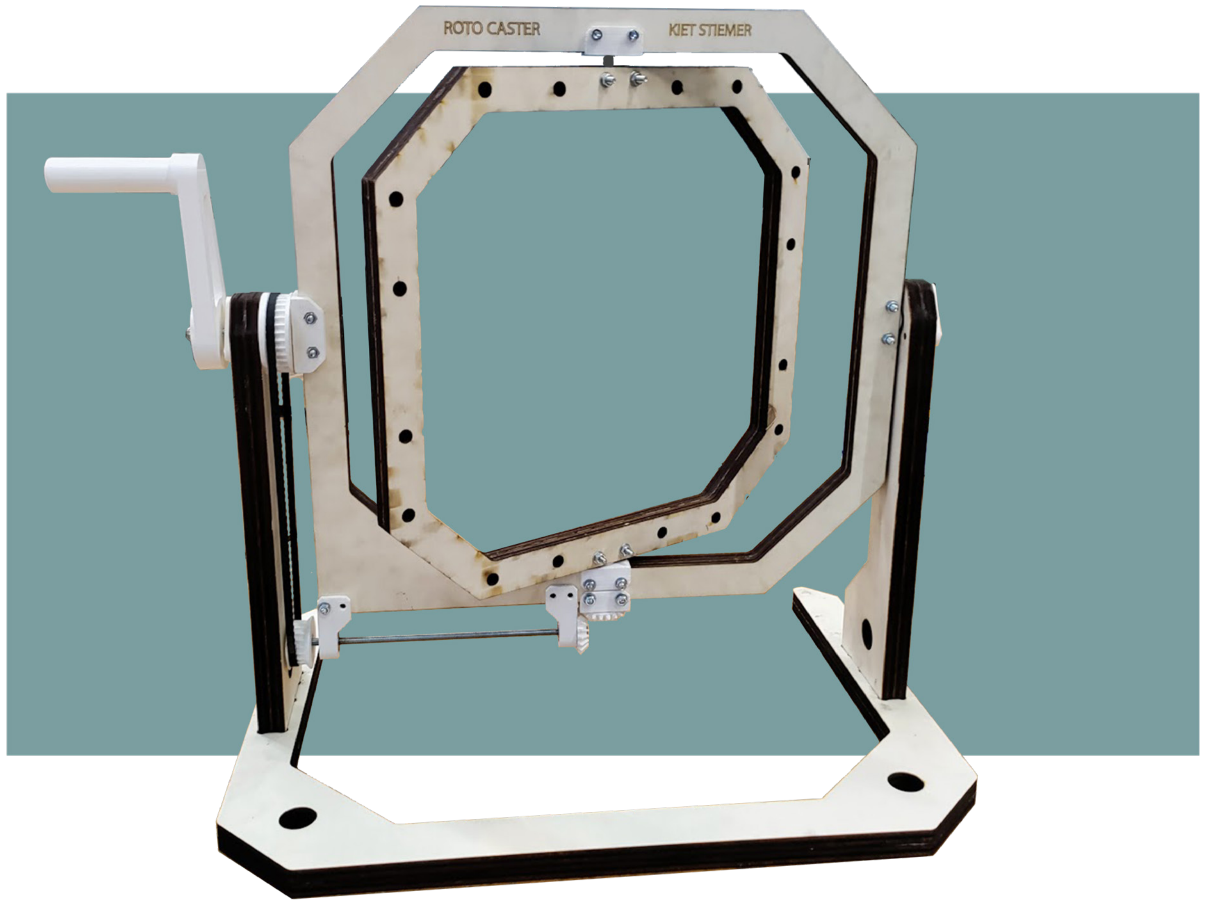
With a 3D printed mould and a glue gun, plastic injection moulding could be simulated. If making sure the hot nozzle does not touch the PLA mould directly, this works fairly well. With the first iteration it is visible the heat of the glue gun shut the small spout in the mould quickly. Simultaneously, the effect this creates is interesting for a student to see as it is visible the glue is pushed around the hole feature towards the bottom and fills from there. This is the case because glue is very viscous and the process is slow. With normal injection moulding, the mould fills rapidly with high pressure pushing out all the air through vent channels before the plastic can fill up from the back to the front, trapping in air. In the second iteration the mould filled up almost all the way, but clearly there is trapped air in the mould. The small feature that creates a hole in the final product also blocks the flow. When removing the product, it takes these small pillars with it breaking them off. This could of course easily be fixed by making it bigger and stronger.
This process also shows that cooling time is important, as when the mould was opened quickly after injection, the glue was still soft and runny. With a plastic mould, this is hard to do. However, again this is a slower process, giving students more time to grasp what is happening. What improves this educational value even more is the use of an acrylic, laser-cut mould, so students can see what is happening. The product also came loose easier from this mould.

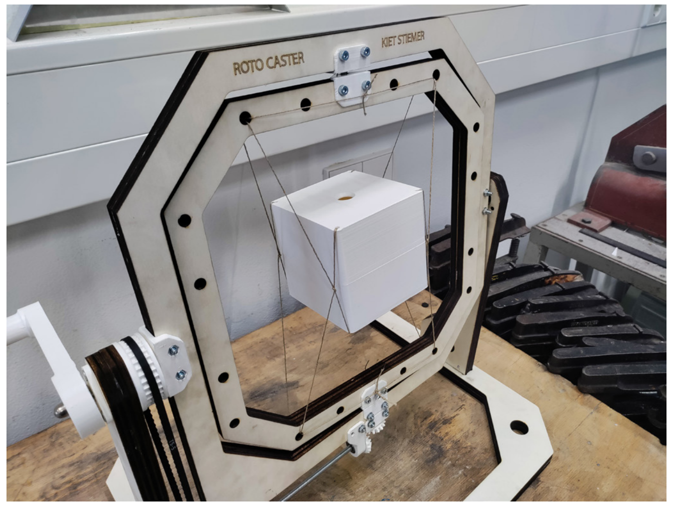
- Candle wax injection moulding

Another way of simulating injection moulding, is with candle wax. This process is also safer, as the heat necessary to melt the wax is relatively low. With a stainless steel syringe, the wax can be molten with a heat gun while blocking the nozzle. Then, the student can attach the mould, open the nozzle and quickly press down the handle of the syringe, pushing in the liquid wax. The advantage of this over the glue is that candle wax does not stick as much to the mould, not requiring as much separating agent (silicone spray was used). It is also possible to actually use some pressure with this method. The result shows that the mould did indeed fill up better than the glue version, but still there is a cavity. It is also recommended not to use such a small part, as the part easily breaks when trying to get it out of the mould.
Candle wax injection is a pretty accessible process, keeping in mind that it is quite messy, however. It would definitely be suitable for further exploration though.

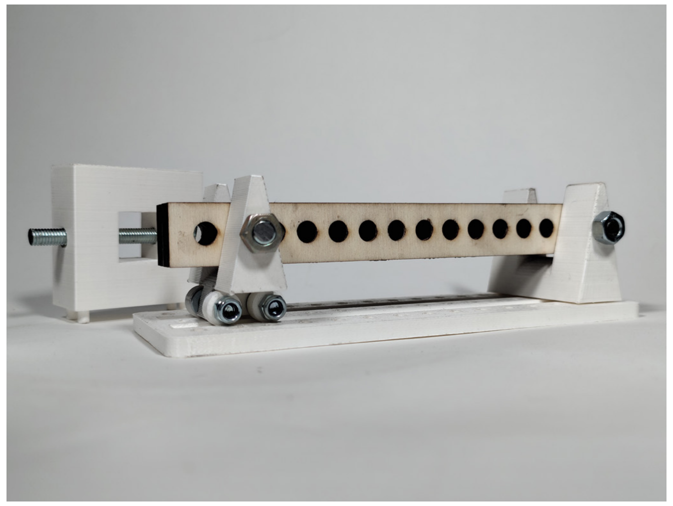
- Candle wax rotation moulding






Partially based on an idea and files by The Practical Engineer (2022), a small rotational moulding device was build. The process is manual and can be used for silicone casting, however, it was used for candle wax again. With rotational moulding, hollow product can be created. In this case, the user has to pour molten candle wax into the mould and start rotating the handle to spin the mould over its three axes. When the wax is not liquid anymore, it can be put in a fridge to cool down as quickly as possible to make the wax set. It was not possible to create a complete product this way, as the product would separate when separating the mould parts. This is caused by a variety of factors like the wall thickness of the product and the texture of the mould.
It still shows the process quite well and has potential for further development. Even with the 'broken' product, a student can see if their wax was distributed evenly over the mould and investigate why this happens. With more complex shapes, they could even discover what features do and do not work with rotational moulding.

- Statics: support types play set




When focusing more on the subject of statics, different ideas were created. One that was prototyped is this 'play set' type of product. In statics, there are three mainly used supports in theory and exercises, being the fully fixed support, the hinge and the roller. With a set that also visually resembles these supports, a student could play around with different setups that occur in their book. When using a beam to connect them, they could apply some type of load to it to see and feel what happens. Especially when using a flexible material for this beam, it can be seen what effect the different supports have on the bending of the beam.

Appendix E. Questionnaire

E.1 Insight section

A part of this section were questions about materials and manufacturing, another part about the fundamental subjects like statics, shear force & bending moment lines and stress & strain.
There were two questions asking directly for the material of a certain object, like the outer part of a car and a mug. The mug is made from stainless steel, but only 17.4% of participants had this correct. The majority answered aluminium, which is somewhat understandable looking at the picture (Figure 75), but it is stainless steel because it is less susceptible to corrosion due to e.g. acidic liquids. When asked how they would determine if it was aluminium or not, all participants gave reasonable methods.

Figure 75: Stainless steel mug

Counting aluminium and steel both as correct answers for the question about a car's body, 90.9% answered correctly. What stands out however is the fact that for the question "how thick is this material?" only 13.6% gave a logical answer. All others overestimated the thickness by a large margin.
On the topic of manufacturing, there were three questions. Two of them were directly asking the manufacturing process for certain products, one was vacuum formed packaging material and the other a rotation-moulded toy car. The first was answered correctly by 43.5% of participants, the second by 23.5% (the majority chose injection moulding). The other question was to determine what method would be the cheapest and fastest to produce 50 barbecues, resulting in 73.9% correct answers.

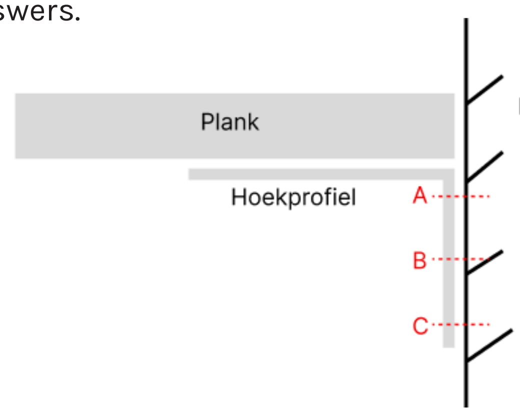


Figure 76: Choose the optimal location for a screw

Then on statics there was a question to indicate where you would place a screw in Figure 76, 82.6% had this correct and 50% gave a correct explanation for their choice. Other questions about external forces were to indicate which orientation of the beam profile in Figure 77 has the most resistance against deformation (B is correct). Here, 68.2% chose correctly.

Figure 77: Choose correct orientation

Only 31.8% answered all three correct in the question where they had to indicate tension, compression or no stress in point A, C and F (Figure 78).

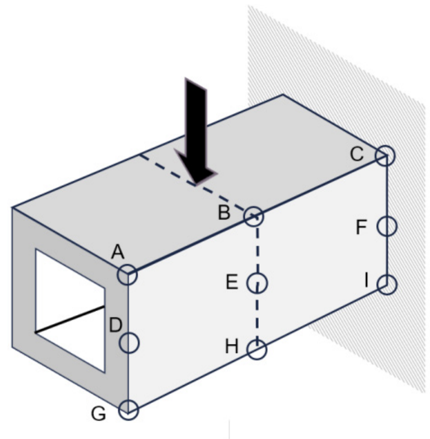


Figure 78: Indicate tension, compression or no stress

When asked to indicate the correct shear force and bending moment diagram for a given load situation, respectively 31.8% and 40.9% answer correctly. This number is low per diagram, but even lower is the amount of participants that have both correct: 21.7%.
Lastly, 94.1% of the participants correctly indicated curve B (Figure 79) belonging to steel when given the options ceramics, rubber or steel.

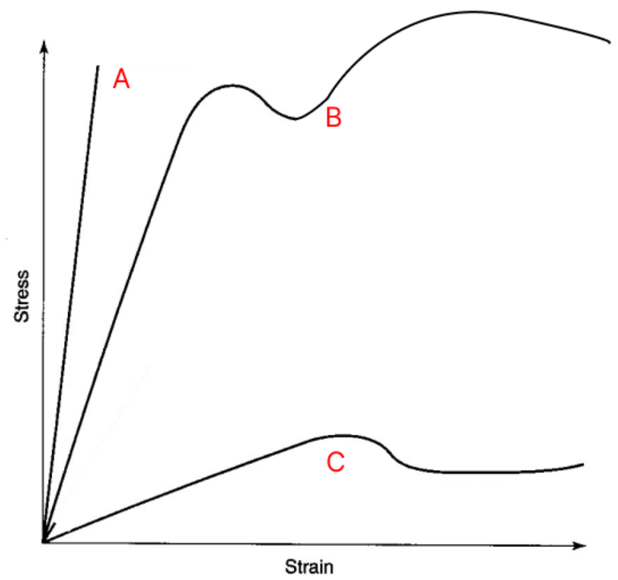


Figure 79: Stress-strain curve

E.2 General section

In this section, they were asked about subjects like the existing LETT machine, some personal data, experience with tinkering and the workshop, their view on the bachelor, UPE and use of obtained UPE knowledge.

59.1% of the participants used the LETT at least once. A few of them indicate a positive experience, the others are only moderately enthusiastic. Something that is often indicated is that the fixing of samples in the grip was a hassle and took a lot of time. The samples also quite often rip at the fixture, causing inaccurate measurements.

The next question was about working in the PMB (the faculty's workshop) and what machines participants used. The majority have used the 3D printers and/or laser cutter. From these 14, six indicated they like to work in the PMB and four they never did but would like to. In total, the first was indicated by 34.8% and the latter by 30.4%.

When asked to indicate what type of prototypes they made, 60.1% indicates they made prototypes for both technical and visual purposes. Only 3 people never made physical prototypes.

The participants were also asked to indicate how they view the bachelor program on a scale of 1 (theoretical) to 10 (practical). This data has been ordered in Figure 80. What it shows is what each participant indicated: the bachelor currently, how they wish it would be and the difference between these. Negative numbers correspond with 'theoretical', positive with 'practical'. The majority of 65.2% would like the bachelor program to be more practical.

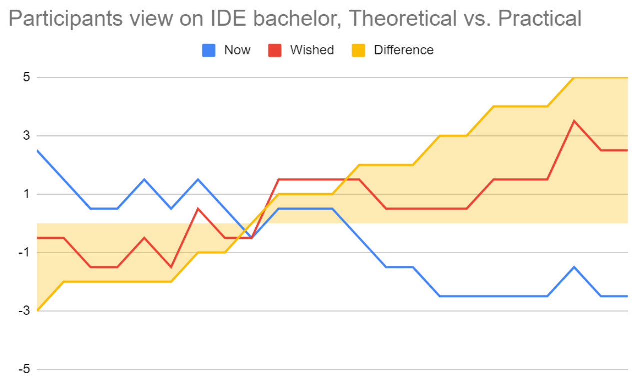


Figure 80: View on IDE bachelor

Furthermore, they were asked what subjects of UPE they found most difficult. The results are shown in Figure 81. The top three are clearly the fundamentals of engineering.

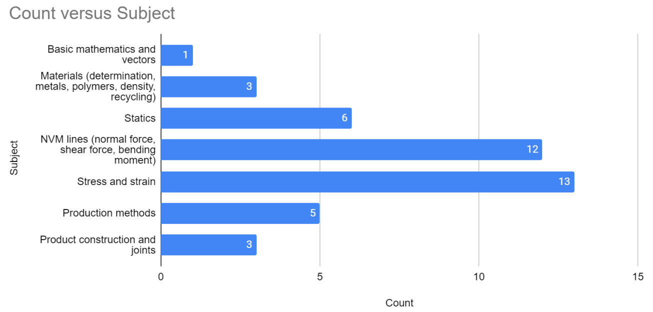


Figure 81: Most difficult UPE subjects as indicated by participants

When asked why they chose their answers, there is no clear reason that occurs most often. The answers range from abstraction and absence of preexisting knowledge for NVM lines, to not getting enough time to internalise something, to having to remember a lot for production methods.

Finally, the participants were asked what subjects they already applied outside of UPE. Their answers are divided into categories and shown in Figure 82.

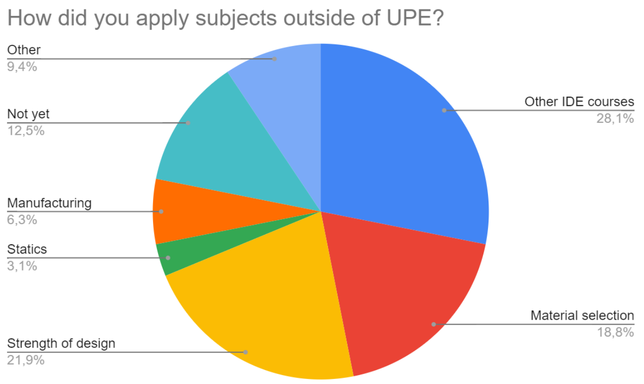


Figure 82: UPE knowledge applied outside of the course

Appendix F. Sampling of statics exercises

Chapter:	3.3	4.4	4.5	4.6
Stress/strain	25	24	9	19
Leverage/balance	23	9	6	8
Total:	48	33	15	27

Chapter:	4.7	5.4	5.7	6.6
Stress/strain	17	34	21	42
Leverage/balance	0	21	1	21
Total:	17	55	22	63

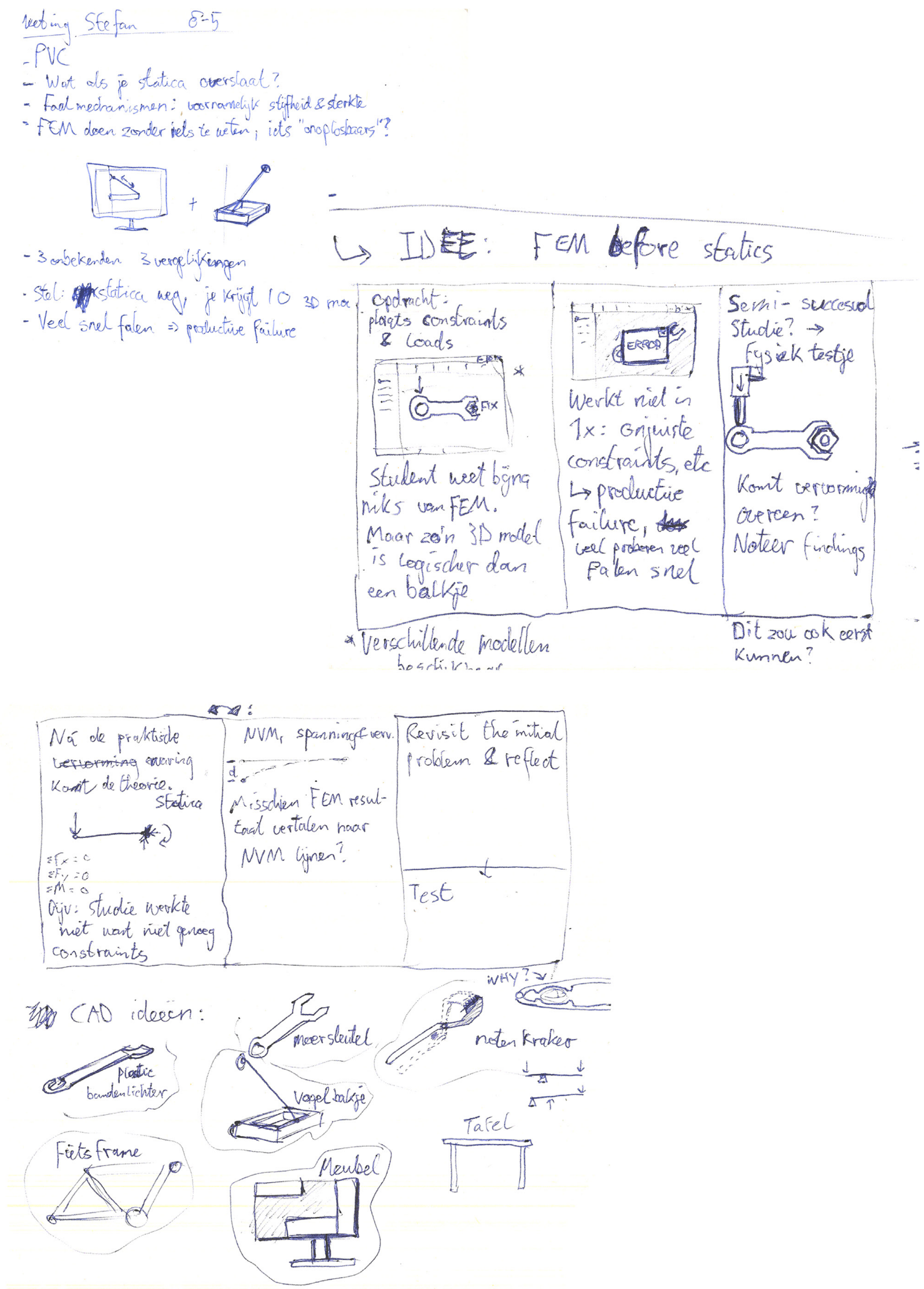
	Total	Ratio
Stress/strain	191	68,21%
Leverage/balance	89	31,79%
	280	

Appendix G. Full PoR

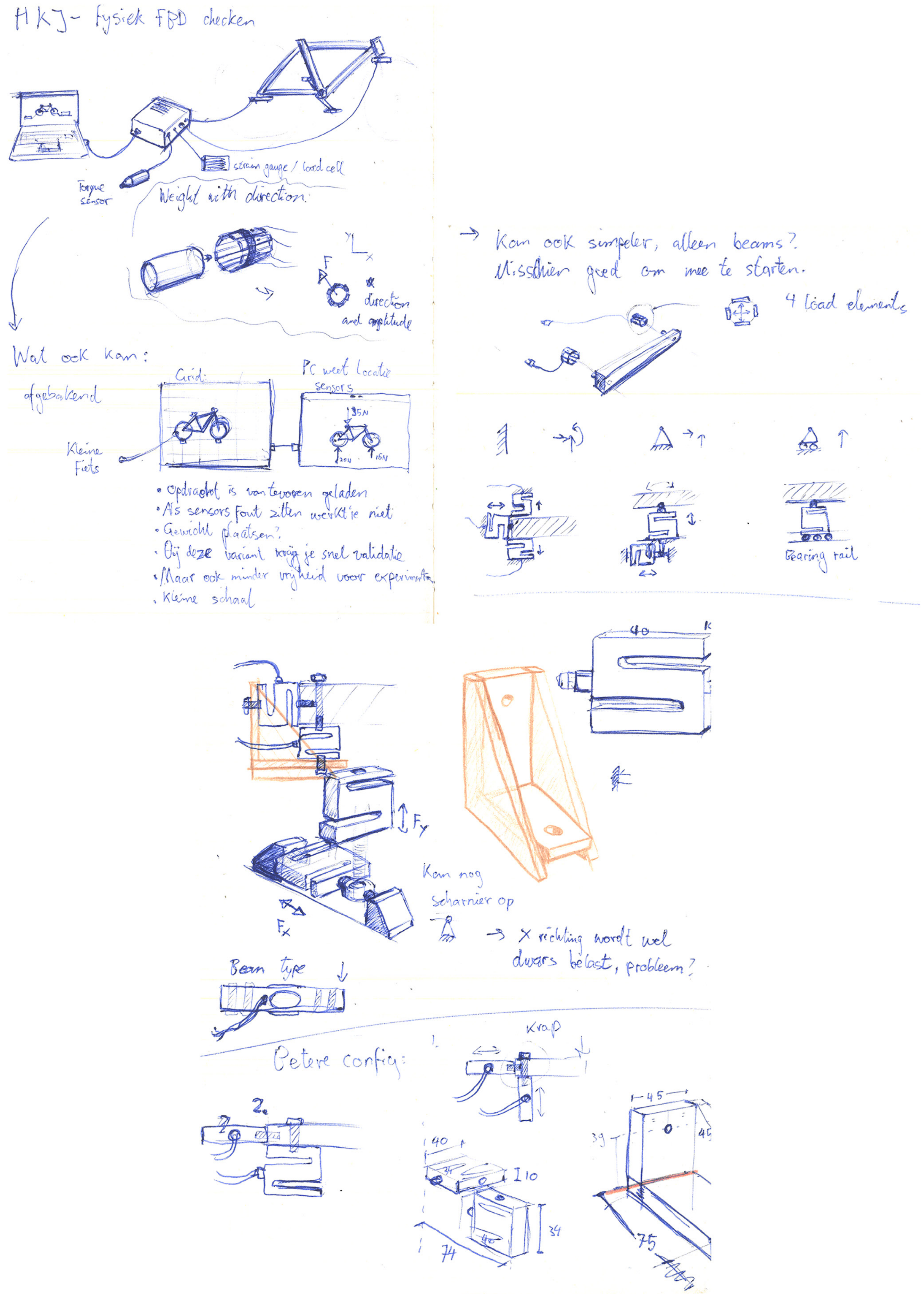
	Requirement	Status
R1	The design and assignment module must enable the Productive Failure approach	Achieved
R2	Must offer a physical, hands-on experience in statics and beam bending	Achieved
R3	Must be scalable to 20 units	Achieved
R4	Cost must stay under €500	Achieved
R5	The design and assignment must be structured so that they can be fully used and completed within a 4-hour afternoon workshop	Achieved
R6	Must improve the retention time of students over a traditional approach	In progress
R7	The assignment module needs to follow the structure as suggested in the Productive Failure Design Cycle	Achieved
R8	The design must be accessible to at least two persons at the same time	Achieved
R9	The design must require students to manually set up an experiment with the machine (no plug-and-play)	Achieved
R10	The design must incorporate elements that enhance students' intrinsic motivation ("wantivation") by ensuring that they perceive the activity as enjoyable and interesting	Achieved
R11	Load application must be possible in steps of 1 N	Achieved
R12	The design must provide a way of visualising the reaction moment in cantilever beam supports	Achieved
R13	The design must provide a way of measuring beam deflection with a resolution of 1 mm	Achieved
R14	The maximum relative error between expected and measured deflection values must be 30%	Not achieved
R15	The design must allow users to fix different materials	Achieved
R16	The design must allow users to fix different profiles	Achieved
R17	Must withstand intensive use for two weeks per year by inexperienced students, at least 5 years before maintenance is required	In progress
R18	Maintenance must be possible with standard tools	Achieved
R19	Must not weigh more than 10 kg to make transport in the faculty possible	In progress
R20	Must fit on a standard desk in an IDE studio	Achieved
R21	The dimensions must be so that the user can stand in an ergonomic posture while using the design	Achieved
R22	Must be manufacturable in under 4 hours, starting from unprocessed parts	In progress
R23	Electronics with open contacts must be shielded for safety	Achieved
R24	The risk of fingers getting stuck or pinched must be mitigated	Achieved

Appendix H. Concept ideation sketches

In the following pictures some ideation that preceded the most promising concepts is shown. Ideation on digital/physical concepts:



Ideation on physical translations of statics:



Appendix I. Concepts

Two other concepts that are a first iteration of final concepts from chapter 7 Concept development.

I.1 FEM before statics

The first concept is one that is less physical and instead revolves around the Finite Elements Method (FEM). This is a numerical technique used to solve complex engineering and mathematical problems, particularly those involving partial differential equations. It works by breaking down a large, complex system into smaller, simpler parts called "finite elements," which are then analysed individually and assembled to predict the behaviour of the entire system. FEM is commonly used in fields such as structural analysis, fluid dynamics, and heat transfer, allowing for precise simulations of physical phenomena.

If it can be used to solve complex problems, it can also solve simple problems. Therefore this concept is making the student perform a FEM simulation in SolidWorks (used at the IDE faculty already). This could give students the opportunity to digitally experiment with the bending of beams, with the result of also learning the application of statics. It is way more stimulating to work with such simulations than to look at abstract, quite boring FBD's (like the ones in Figure 18b and Figure 19b). The basic scenario of this concept is as shown in Figure 83.

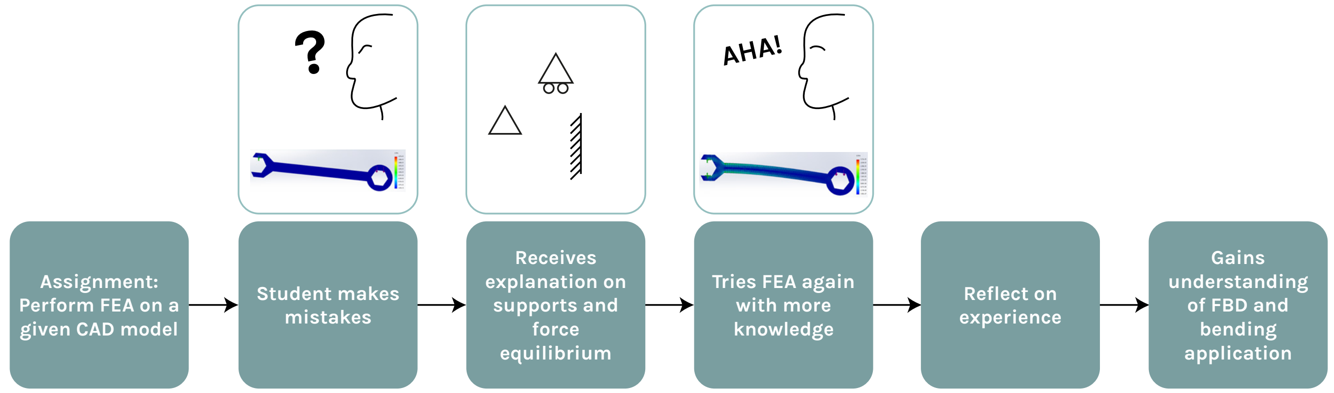


Figure 83: Scenario for concept "FEM before statics"

To make the connection to reality, CAD models of common products can be provided, like the shown wrench. Other options could be nut crackers, bicycle tire lifters, a bicycle frame or furniture. Visible is also the way Productive Failure is implemented. The student would only get basic instruction on the software, but not how to perform a correct simulation. This way, they are left to experiment themselves. Mistakes they could potentially make, among others, is choosing the wrong support, placing them incorrect or unrealistic, making the situation statically under or over determined, placing the load in an unrealistic spot or choosing an unrealistic low or high load. After receiving theory and more instruction, they can redo their simulation and perform a successful one. In Figure 84, a simple FEM simulation the students can come across is shown.

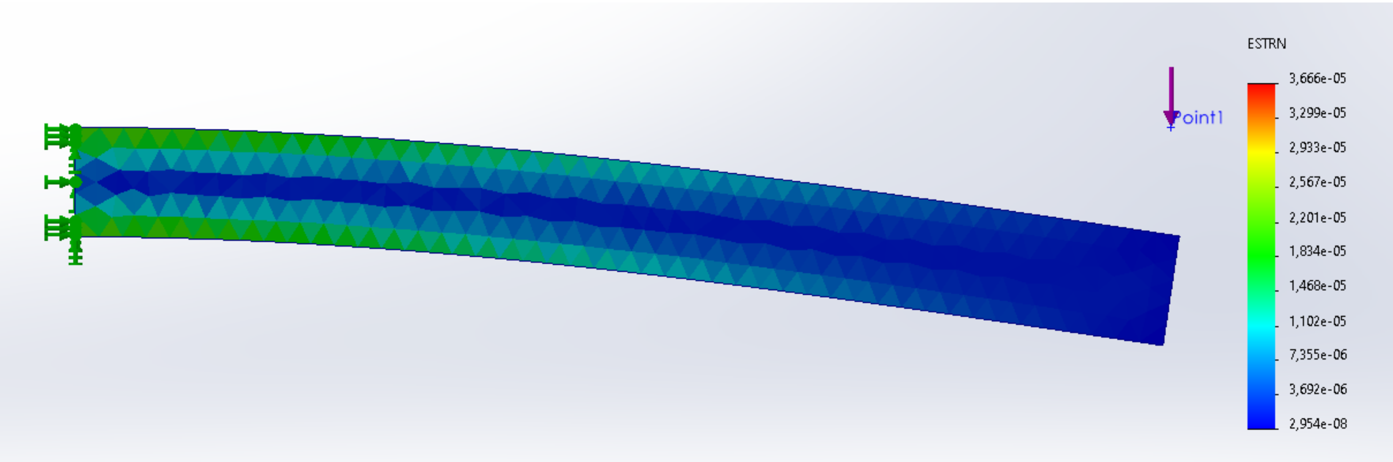


Figure 84: Simple static simulation of a cantilever beam

In a SolidWorks "static study", the user has to indicate where the product is supported and how, and where a (distributed) load or moment is placed. This can make a bridge between FEM and statics. It also gives the student experience in translating reality to a virtual environment. As seen in Figure 84, the result of the simulation clearly shows where the stress in the model is the largest. This is valuable knowledge for a designer, as they have to take into account where their designs have to be stronger, or where they can save material.

I.1.1 Discussion
This concept meets most requirements, or it is realistic to expect to do so when developed further. However, the requirement of offering a physical, hands-on experience is not met. It lacks a physical element.
Besides this, it is tested how many steps it takes to perform a simple simulation to get a result like in Figure 84. This is quite a lot, meaning it would still require lots of instruction for the student to even be able to start experimenting. This means the threshold is possibly too high to perform this in a productive failure workshop.

I.2 FBD machine - real products
Looking at more physical solutions, another concept is created. This concept is a device that integrates multiple sensors and can be connected to a laptop with accompanying software. This serves the purpose of enabling students to check their FBD's. Right now, it is hard to check if your FBD is correct, unless you solve the system of three unknowns and three equations. Even then, a student does not know how realistic their solution is. This concept will allow them to place the sensors, being load cells and possibly a torque sensor, at the same positions they placed their supports in the FBD (Figure 85). The software could be partially copied from the LETT machine,

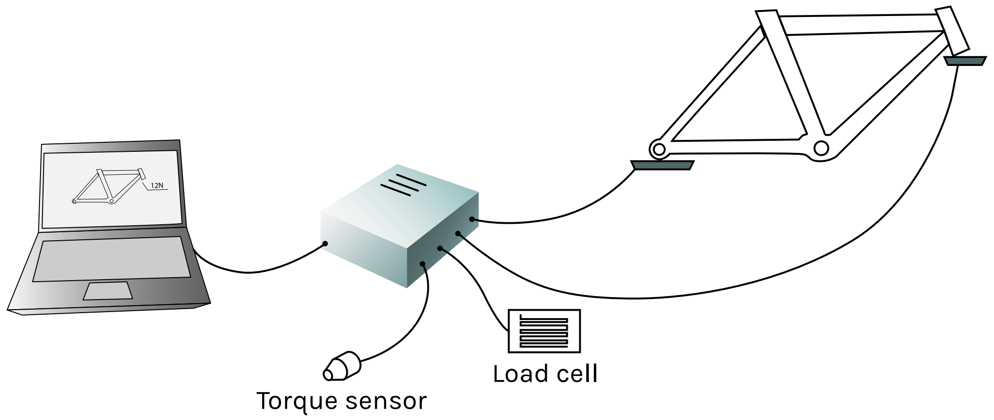


Figure 85: An example of a situation where the FBD checker can assist

as that already has functionality to read load cells. It would just need a different Graphical User Interface (GUI), and could possibly have a function to automatically compare to the theoretical FBD. Besides the shown bike frame, other objects like a foldable chair, beer opener or gym equipment could be analysed. These suggestions are deliberately relatable objects for students.
Load cells like the one in Figure 86 could be used. The one shown is a beam type load cell, which in the shown configuration is a simple scale. They are not hard to connect to an Arduino to read their value.

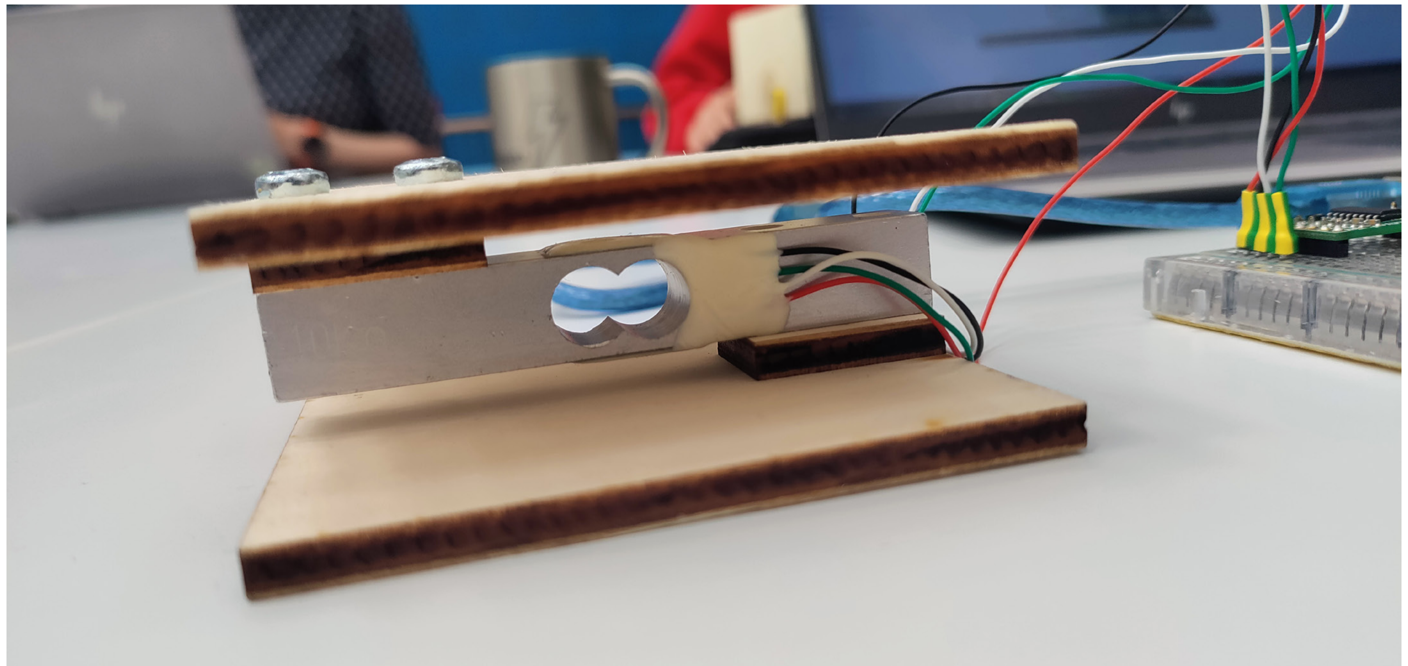


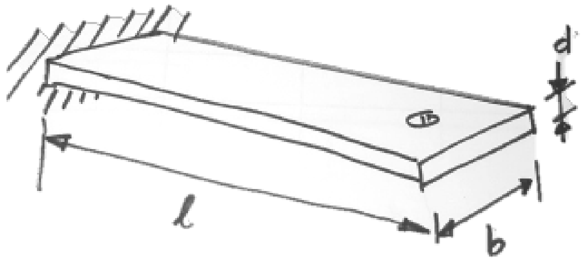
Figure 86: Beam-type load cell in scale configuration

I.2.1 Discussion
For full experience, the concept needs to be equipped with a sensor that measures in two directions and allows rotation (hinge support), one that only measures one direction and allows rotation and motion in the other direction (roller support) and a sensor that measures both directions, torque and prevents all rotation and motion (fixed support). This is quite challenging however, as they at the same time need to be able to be connected to objects like the bike frame in Figure 85. It was also found it is hard to get affordable static moment sensors. There are sensors that can measure force and torque with 6 axes, but they cost close to EU3000 (ME-Systeme, n.d.).
To omit the need for a moment sensor, situations without fully fixed supports could be considered. This however would limit the functionality and the counter moment is exactly a hard to grasp phenomenon for students. Lastly, it is chosen to take bending of beams into consideration with the concept design. This concept does not have an element of bending.

Appendix J. Educational module

1. The core concept of the workshop is LO1.5 "Apply the basic principles of mechanics of materials and materials science in the most common construction situations within the context of product design".
2. Next, an exam question that relates to the EDA is chosen. A fitting example would be the question in Figure 87, coming from the 2022 UPE resit exam (B. Flipsen, personal communication, March 26, 2024).

De hiernaast afgebeelde lamp wordt opgehangen aan een constructie, die bestaat uit een koolstofstalen plaat (low carbon steel). De lengte van de plaat is l=300 [mm], de breedte is b=20 [mm] en dikte is d=3 [mm]. We nemen aan dat de constructie ingeklemd is opgehangen aan de muur.



We willen de stalen plaat uitvoeren in een ander materiaal, namelijk multiplex (plywood). De nieuwe plaat mag net zoveel doorbuigen als de stalen versie, maar niet meer. De lengte en breedte blijven gelijk, en alleen de dikte van de staaf mag worden gevarieerd.
Maak gebruik van Granta Edupack level 2, en neem de gemiddelde waarden uit de tabel.

2. Wat is de minimale dikte van de nieuwe houten plaat in millimeters [mm]? Rond af op 1 decimaal nauwkeurig. Laat duidelijk zien hoe je aan het antwoord komt. [2 punten]

Figure 87: Exam question about redesigning a product with a cantilever

3. Real application: Designing wall mounted products like bicycle rack, lamp, shelves, TV mount. Designing furniture like chairs with armrests or designer fauteuils. Constructions with overhang in the built environment. Designing boom arms for e.g. microphones or dentist or surgery equipment. Designing mechanical constructions in automotive or aerospace engineering. Street furniture or infrastructure like benches, street lanterns or poles. Snap joints.
4. Problem: Aeroplane seat's armrest must be as light as possible, as every gram less saves a bit of fuel. At the same time, it must also be strong and be able to hold up in constant use in aeroplanes. It must not bend too much under the weight of someone leaning on it, or even accidentally sitting on it.
5. Solution: Possible wrong solutions students can come up with are listed here.
   Student thinks only the material has influence on the deflection
   Student does not know what difference the position of the load makes
   Student chooses mostly based on intuition, e.g. choosing an unnecessarily heavy material profile as that does not bend much
6. Redefine: You are asked to find a part that can be used in the construction of the armrest of an aeroplane seat. It needs to be as light as possible and resist the force of a human's arm leaning on it. You have gathered a selection of options, all with different material and/or profile. The armrest is only allowed to deflect at most 10 millimetres, as more will make the armrest uncomfortable.

J.1 FBD machine - real products

Who: Student groups of 4 to 5 students
Where: A studio in the IDE faculty
When: One afternoon from 13:45 until 17:30
What: Provided per group is a table with chairs, the EDA including samples, some basic tools and measuring devices, whiteboard with markers and one large screen for the whole studio

1. Prepare
   Formative exam, questions related to the lecture (10 minutes)
2. Ideate
   Problem introduction: group of students is asked to find out what factors influence the bending of the samples they have been given
   Guided brainstorm: brainstorm possible solution strategies with the group, how to find variables and constants that have influence
   Select and try: the group selects an approach and gets to work with the EDA
   Share: the groups share their findings to the rest of the studio
3. Prototype
   Direct instruction: video with explanation of the deflection formula and its variables and constants is shown, plus instruction how to measure this
   New assignment: the groups are now instructed to compare theoretic values to real values, do they match or are there deviations
   Try again: the groups will now calculate the theoretic values. To do so, they need to measure the geometry of their samples and find the Young's modulus in Granta EduPack
4. Evaluate
   Wrap-up: evaluate key findings, reflect on process and the role of the EDA

J.2 Suggestions for other assignments

1. Find out when the relative error becomes unacceptable - until where are the deflection formulas valid? What influences this?
2. Find out when a material starts deforming plastically instead of elastically - can you say something about the stress strain curve?
3. Bring a real life beam type part - can you predict how (much) it will bend? Is that accurate?

Appendix K. Accuracy assessment

A relative error value was calculated by using:

$$error = \frac{measured - expected}{expected} \times 100\%$$

The results of the first test are shown in Table 11. It also shows the absolute error.

Table 11: Accuracy test with F = 11.0, rangefinder

Description	Deflection (mm)	Measured (mm)	Abs. error (mm)	Rel. error
Aluminium rectangle horiz.	11.7	14	2.3	20%
Aluminium rectangle vert.	1.3	4	2.7	209%
Aluminium rod round	4.7	8	3.3	71%
Aluminium tube round	6.3	8	1.7	27%
Aluminium L profile	6.2	11	4.8	77%
Aluminium U profile [	2.6	4	1.4	51%
Aluminium U profile upside down	3.8	7	3.2	86%
PVC rod round	96.6	46	-50.6	-52%
Brass rod square	63.0	63	0.0	0%
Steel rod round	52.2	64	11.8	23%
POM rod round	34.6	42	7.4	21%

To find out if the accuracy is different under a higher load, the same test was performed, but with F=15.9N. The results are presented in Table 12.

Table 12: Accuracy test with F = 15.9, rangefinder

Description	Deflection (mm)	Measured (mm)	Abs. error (mm)	Rel. error
Aluminium rectangle horiz.	16.9	20	3.1	18%
Aluminium rectangle vert.	1.9	6	4.1	220%
Aluminium rod round	6.8	12	5.2	77%
Aluminium tube round	9.1	10	0.9	10%
Aluminium L profile	9.0	19	10.0	111%
Aluminium U profile [	3.8	6	2.2	57%
Aluminium U profile upside down	5.4	9	3.6	65%
PVC rod round	140.0	88	-52.0	-37%
Brass rod square	83.3	102	18.7	22%
Steel rod round	75.6	91	15.4	20%
POM rod round	50.1	54	3.9	8%

As mentioned, another measuring method was used as well. The results of using a height gauge and measuring the neutral axis of the samples are shown in Table 13. In these results, a second absolute and relative error are included. These are derived from adding the theoretical deflection caused by the samples' own weight to the theoretical deflection caused by the load. The deflection caused by own weight is considered to be a distributed load on the beam.

Table 13: Accuracy test, height gauge

Description	F (N)	Deflection (mm)	Measured (mm)	Abs. error (mm)	Rel. error	Abs. Error 2 (mm)	Rel. error 2
Aluminium rectangle horiz.	11.0	11.7	16	4.3	37%	4.1	34%
Aluminium rectangle vert.	11.0	1.3	5	3.7	286%	3.7	277%
Aluminium rectangle vert.	20.7	2.4	6.3	3.9	158%	3.8	155%
Aluminium rectangle vert.	35.5	4.2	10.5	6.3	151%	6.3	149%
Aluminium rod round	11.0	3.9	6	2.1	53%	2.0	51%
Aluminium tube round	11.0	6.3	9	2.7	43%	2.7	42%
Aluminium L profile	11.0	6.2	15	8.8	141%	8.7	139%
Aluminium U profile [	11.0	2.6	6	3.4	127%	3.3	124%
Aluminium U profile upside down	11.0	3.8	9	5.2	140%	5.2	136%
PVC rod round	11.0	96.6	60	-36.6	-38%	-37.9	-39%
Brass rod square	11.0	57.5	64	6.5	11%	5.7	10%
Steel rod round	11.0	47.6	55	7.4	15%	6.8	14%
POM rod round	6.0	17.5	21	3.5	20%	3.2	18%
POM rod round	11.0	31.8	39	7.2	22%	6.8	21%

Appendix L. User test 1: usability

L.1 Method

1. **Objective**
   To evaluate the basic usability of the bending test machine.
2. **Participants**
   a. Number of participants: 3-4
   b. Background: from the IDE faculty, basic knowledge of mechanics of materials, no experience with this machine
3. **Environment**
   a. Applied Labs or a studio
   b. Equipment: Bending test machine, beam samples, hangers, weights, instructional materials, laptop (with sheets for data recording + survey)
   c. Bending test machine should not be setup with clamp installed, participants have to do this themselves.
4. **Materials**:
   a. Samples: 9 different samples, with two of them having two possible orientations
   b. Load Application Tools: Hangers and weights.
   c. Measurement Tools: Torque sensor, ruler for measuring beam length, digital ruler for deflection measurement (all built into device).
5. **Tasks**
   a. Two phases, one without instruction to research how intuitive it is to use, and one with complete instruction.
   b. In advance: let the participant fill in some anonymous background information in the survey.
   c. Phase 1 - no instruction
      i. Assignment: "You are designing a chair and for the arm rest you have gathered different materials and shapes. Choose three samples and try to figure out which sample has the least deflection. Use the machine and accompanying Excel sheet."
      ii. Data collection: They can use the excel sheet to calculate things if they want to, but mainly to record their measurements.
      iii. Evaluation: the participant answers some questions in a Google Forms survey
         1. Did you understand the assignment?
         2. How was your understanding of the general function the machine has?
         3. How was your understanding of the individual parts of the machine?
         4. How was your understanding of the Excel sheet?
         5. Any general difficulties?
   d. Phase 2 - instruction
      i. Provide a detailed explanation of how the machine works, the purpose of the torque sensor, and the correct procedure for setting up and using the machine.

ii. Explain the relationship between the applied load, deflection, and torque.
iii. Assignment: do the same thing again, see if you can improve the accuracy.
iv. Evaluation: The participant answers the remaining questions in a Google Forms survey
    1. Rate the ease with which you were able to fix the material in the machine.
       Remarks?
    2. Rate the ease with which you could apply a load on the sample.
       Remarks?
    3. Rate the ease with which you could measure the deflection.
       Remarks?
    4. Did you use the torque sensor?
    5. Do you see any use for the torque sensor?
    6. Any last comments?

6. **Data types**:
    a. Quantitative data: the measurements users took during their session in the excel sheet.
    b. Qualitative data: summary responses, verbal feedback, observations.

L.2 Procedure

1. Introduction (5 minutes)
    a. Start timer
    b. Explain goal of the machine, but not its specific functions
    c. Explain 2 phase setup of test
    d. Explain data collection and consent form
    e. Ask to think out loud
2. Phase one (20 minutes)
    a. Explain assignment
    b. Let participant use the machine
    c. Let participant fill in the first questions of the survey
3. Phase two (20 minutes):
    a. Explain the machine completely and instruct the intended use
    b. Let the participant repeat the assignment (with different samples)
4. Final phase (10 minutes)
    a. Let participant answer the final questions of the survey
    b. Thank participant and give reward
    c. Stop timer

L.3 Consent form

Usability of bending test machine

This research is conducted as part of the MSc study Industrial Design Engineering at TU Delft.

Student: Kiet Stiemer

Informed consent participant

I participate in this research voluntarily.

I acknowledge that I received sufficient information and explanation about the research and that all my questions have been answered satisfactorily. I was given sufficient time to consent my participation. I can ask questions for further clarification at any moment during the research.

I am aware that this research consists of the following activities:

1. Using a concept for a bending test machine, uninstructed, while being observed;
2. Using the same concept, now with instructions;
3. Filling in a questionnaire.

I am aware that data will be collected during the research, such as notes, photos, video and/or audio recordings. I give permission for collecting this data and for making photos, audio and/or video recordings during the research. Data will be processed and analysed anonymously (without your name or other identifiable information). The data will only be accessible to the researcher and their TU Delft supervisors.

The photos, video and/or audio recordings will be used to support analysis of the collected data. The video recordings and photos can also be used to illustrate research findings in publications and presentations about the project.

I give permission for using photos and/or video recordings of my participation:
(select what applies for you)

- ☐ in which I am <u>recognisable</u> in publications and presentations about the project.
- ☐ in which I am <u>not recognisable</u> in publications and presentations about the project.
- ☐ <u>for data analysis only</u> and not for publications and presentations about the project.

I give permission to store the data for a maximum of 5 years after completion of this research and using it for educational and research purposes.

I acknowledge that no financial compensation will be provided for my participation in this research.

With my signature I acknowledge that I have read the provided information about the research and understand the nature of my participation. I understand that I am free to withdraw and stop participation in the research at any given time. I understand that I am not obliged to answer questions which I prefer not to answer and I can indicate this to the research team.

The researchers take the applicable COVID-19 measures into account. I confirm to respect the COVID-19 measures taken and will follow instruction about these provided by the researchers.

I will receive a copy of this consent form.

______________________	______________________
Last name	First name
___ / ___ / 2024	______________________
Date (dd/mm/yyyy)	Signature

L.4 Findings

1. The assignment causes the participants to choose based on their knowledge and insight; as the aluminium samples are thicker they are automatically preferred over the thinner brass and steel profiles.
2. The torque sensor shuts down to save battery quite often, this is sometimes discovered only after already applying a load.
3. The torque sensor displays a set value for an alarm when no load is applied, as soon as the torque surpasses 0.9 N.m it starts displaying the measurement; this can be confusing at first.
4. The torque sensor has quite a few buttons and modes, and as it only displays the set alarm value in rest, this causes some participants to try all the sensor's functions; this distracts from the process.
5. The "zero" function of the digital ruler is not found directly.
6. Some participants note the length of the beam from the axis of the torque sensor to the end of the beam for their calculation, while they have to take the length starting from the outside of the grip; this can be confusing as the moment is in fact related to the length starting from the axis.
7. Other participants understand which length they have to use automatically; the clear indication of S and L on the grips and machine help with this.
8. The interaction with the digital ruler is hard, it is difficult for participants to position it correctly and get a good reading; a contrasting background with guides is suggested as improvement.
9. Sliding the ruler horizontally is not smooth; the fact the participant needs a tool to loosen and fasten the screws is very unintuitive.
10. The ruler on the top of the device is handy, but it is relatively far away from the test sample; this makes it hard to get an accurate measurement of the length of the beam or position of the load.
11. When the samples are not loaded, they sometimes slightly angle upwards; this makes it harder to get a correct initial position measurement.
12. The need for the torque sensor is unclear in combination with the given assignment; this is confusing, however participants do see a use for it in other situations.
13. Giving some participants a little more instruction than others at the start, it seems there is a fine line between giving no guidance and explaining everything to the point where there's nothing left to explore; the key seems to point out the components and their function, without dictating how they should be used.
14. For this reason, some participants suggest labelling important components; this makes the process more efficient as students do not have to spend time on something they do not learn a lot from.
15. In the questionnaire, participants rated the ease of fixing the samples in the machine an average of 4 out of 5. Applying a load received a rating of 4.3, while measuring deflection was rated lower, at 3.3.
16. In the first phase of the experiment, measuring results had a greater error compared to the theoretical value than in the accuracy assessment. In the second phase, some of the results had an error closer to that of the accuracy assessment.

Appendix M. User test 2: target group

This test's objective is to evaluate how the target group (UPE students) currently uses the EDA in a workshop. This is a final benchmark of the concept and the result is a starting point for further development.

M.1 Structure and material

Who: Pair of two students
Where: A studio in the IDE faculty
Duration: One hour
What: Provided is:
- a table with the EDA including samples (accessible from both sides)
- some basic tools and measuring tools
- pens and paper
- laptop with Excel sheet
    - first tab for first phase (only some measurement suggestions)

	A	B	C	D	E	F
1	EDA user test - participants sheet nr:		1			
2						
3	Measurements phase one					
4	Sample name	Force	Deflection - measured (mm)	?	?	?
5						
6						

    - second tab for second phase (expanded with youngs' modulus and moment of inertia for the available samples + table to compare theory-reality)

	A	B	C
1	EDA user test - participants sheet nr:		1
2			
3	Sample	Young's Modulus (E)	Moment of Inertia (I)
4	Aluminium rod rectangle horiz.	6.9E+10	1.563E-10
5	Aluminium rod rectangle vert.	6.9E+10	1.406E-09
6	Aluminium rod round	6.9E+10	2.113E-10
7	Aluminium tube round	6.9E+10	2.898E-10
8	Aluminium L profile	6.9E+10	2.927E-10
9	Aluminium U profile [-channel	6.9E+10	6.893E-10
10	PVC rod round	3.1E+09	4.909E-10
11	Brass rod square	1.0E+11	2.133E-11
12	Steel rod round	2.1E+11	1.257E-11
13	POM rod round	2.9E+09	6.197E-10

E	F	G	H	I	J	K	L
Measurements phase two							
Sample	F (N)	L (m)	E (Pa)	I (m^4)	Deflection - theory (mm)	Deflection - measured (mm)	
					#DELING.DOOR.0!		
					#DELING.DOOR.0!		
					#DELING.DOOR.0!		
					#DELING.DOOR.0!		
					#DELING.DOOR.0!		
					#DELING.DOOR.0!		
					#DELING.DOOR.0!		

Due to the relative short time that students have, some data and tools are already given in the sheet, like the Young's Modulus and Moment of Inertia. The deflection formula is also already filled in, as calculating these by hand would be time consuming and not as relevant for the test.

Setup:
1. Introduction (5 minutes)
   a. Explain test setup
   b. Fill out consent form
   c. Fill out first questions
2. Start first phase - ideation (20 minutes)
   a. Participants receive assignment
   b. They come up with possible ways to come to a solution
   c. They try it out with the EDA
   d. Share findings with the researcher
3. Second phase - prototype (25 minutes)
   a. Direct instruction: mini lecture on bending of beams and the cantilever
   b. New assignment: compare theoretical with reality
4. Wrap-up - evaluate (10 minutes)
   a. Share findings with researcher
   b. Fill out questionnaire

Assignment:
"For the design of an aeroplane seat, the developers have asked you to investigate how the arm rest can be as light as possible to save fuel, but it cannot bend too much to stay comfortable. Different materials and profiles are available, how do you find out which is the best option? What factors influence the deformation?"

Other material necessary:
Camera + tripod
Consent forms (see Appendix M.3)
Reward for participants (€15 VVV gift cards)

M.2 Assignment and questionnaire

User test 2: UPE students

This is a survey that corresponds with a workshop/prototype user evaluation. The prototype is called Educational Deflection Analyser (EDA) and is a type of "experiential machine". These setups will be more and more deployed in UPE the coming years.

* Verplichte vraag

1. Study programme *

   Markeer slechts één ovaal.

   - [ ] Industrial design engineering
   - [ ] Anders: ____________

2. What year student are you? *

   Markeer slechts één ovaal.

   - [ ] 1st year bachelor
   - [ ] 2nd year bachelor
   - [ ] 3rd year bachelor
   - [ ] 4th+ year bachelor

3. How confident do you feel about solving exercises about statics and mechanics of materials?

   Markeer slechts één ovaal.

	1	2	3	4	5	
I don't know anything	◯	◯	◯	◯	◯	I feel very confident

Phase one - Ideation (20 minutes)

For the design of an airplane seat, the developers have asked you to investigate how the arm rest can be as light as possible to save fuel, but it cannot bend too much to stay comfortable. Different materials and profiles are available, how do you find out which is the best option? What factors influence the deformation?

Use the available machine (EDA), tools and Excel sheet. Only use tab 1 on the sheet.

4. What was your approach to find out which sample fits the requirements the best? *

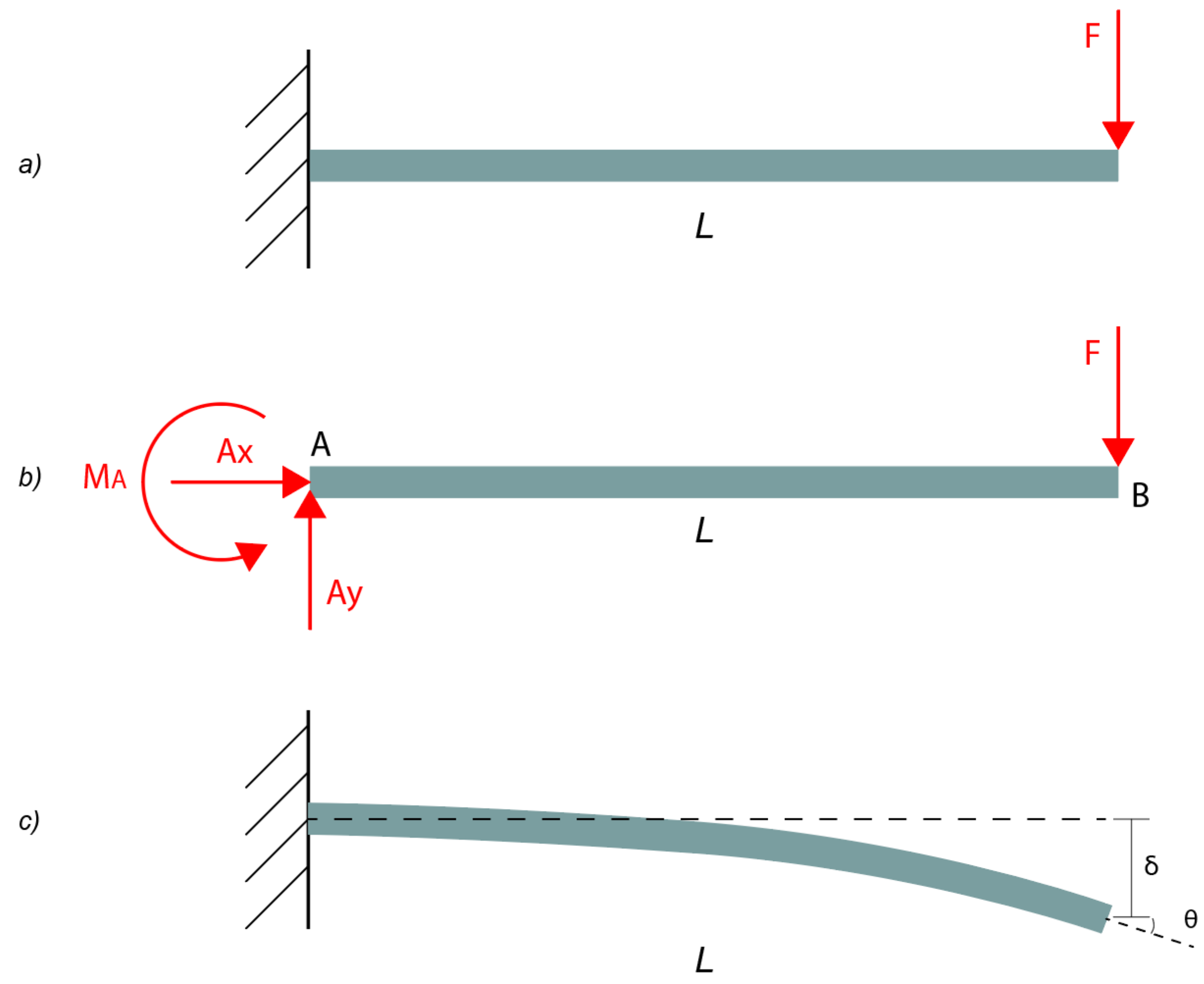
5. What factors influence the deformation of the beam? *

6. What went wrong or was difficult? *

Phase two - Instruction (25 minutes)

A beam that is fixed on one end and free on the other, is called a 'cantilever'. In real life, beams deflect a little bit under load. This is called elastic deformation: the material deforms, but springs back to its original state after the load is not applied anymore. You can compare this to holding a ruler flat on a table with the free end hanging over the edge. The ruler bends when you push it down, but will be flat again after pushing.

In the following image you can see a typical situation (a), the Free Body Diagram or "Vrije lichaamsschema" (b), and the way the beam will deflect (c).



Deformation of beams within the elastic limit (the beam does not permanently deform) can be approximated with formula's. To calculate the deflection of a cantilever beam, with a point load on the free end, we use:

$$\delta = \frac{FL^3}{3EI}$$

Deflection equation
- Delta is the deflection (in metre)
- F is the point load (in Newton)
- L is the length of the beam (in metre)
- E is the Young's Modulus (in Pascal)
- I is the moment of inertia (in metre^4)

The Young's Modulus is a **material** property and the moment of inertia is determined by the **geometry** and orientation of the beam. These properties are given in the Excel sheet for the available samples (use tab 2 now).

7. Were the factors you indicated before you knew the equation correct? If not, what was the difference? *

   Markeer slechts één ovaal.

   ◯ Yes
   ◯ Anders: ______________

Assignment
Your objective is now to calculate the theoretical deflection and compare this with real measurements. This could be useful, because if the theory approximates reality well enough, you can use the equations for design optimisation of the seats armrest.

Use the EDA again for measurements. Use tab 2 on the Excel sheet for further measurement notations and calculations.

8. How well did your calculations correspond with your measurements? *

9. What could cause deviations between the two? *

10. What sample would you choose to design the armrest with? *

Wrap-up

11. Did you learning anything new today?

    Markeer slechts één ovaal.

    ◯ Yes
    ◯ No, I already knew about how beam deflection works and how you can approximate it

12. How much did you enjoy using the experiential machine in the workshop? *

    Markeer slechts één ovaal.

	1	2	3	4	5	
I did not like it at all	◯	◯	◯	◯	◯	I enjoyed it a lot

13. How easy was it to use the EDA with two people? *

    Markeer slechts één ovaal.

	1	2	3	4	5	
Very difficult	◯	◯	◯	◯	◯	Very easy

14. How confident do you feel about what you learned? *

Markeer slechts één ovaal.

	1	2	3	4	5	
I still don't understand anything	◯	◯	◯	◯	◯	Feel very confident

15. Was there a moment during the test in which you felt lost and did not know what to do? *

16. Did you experience any physical discomfort (in terms of uncomfortable postures or heavy loads on your limbs or body)? *

Markeer slechts één ovaal.

◯ No
◯ Anders: ____________

17. What is the deflection formula again? Write it down from the top of your head, do not look back in the questionnaire etc. *

M.3 Consent form

User test of UPE experiential machine

This research is conducted as part of the MSc study Industrial Design Engineering at TU Delft.

Student: Kiet Stiemer

Contact person: Kiet Stiemer, k.g.c.stiemer@student.tudelft.nl, +31 6 30040818

Informed consent participant

I participate in this research voluntarily.

I acknowledge that I received sufficient information and explanation about the research and that all my questions have been answered satisfactorily. I was given sufficient time to consent my participation. I can ask questions for further clarification at any moment during the research.

I am aware that this research consists of the following activities:

1. Using a prototype for an "Educational Deflection Analyser" following a small workshop, during observation;
2. Filling in an assignment sheet and questionnaire.

I am aware that data will be collected during the research, such as notes, photos, video and/or audio recordings. I give permission for collecting this data and for making photos, audio and/or video recordings during the research. Data will be processed and analysed anonymously (without your name or other identifiable information). The data will only be accessible to the researcher and their TU Delft supervisors.

The photos, video and/or audio recordings will be used to support analysis of the collected data. The video recordings and photos can also be used to illustrate research findings in publications and presentations about the project.

I give permission for using photos and/or video recordings of my participation:
(select what applies for you)

- ☐ in which I am recognisable in publications and presentations about the project.
- ☐ in which I am not recognisable in publications and presentations about the project.
- ☐ for data analysis only and not for publications and presentations about the project.

I give permission to store the data for a maximum of 5 years after completion of this research and using it for educational and research purposes.

With my signature I acknowledge that I have read the provided information about the research and understand the nature of my participation. I understand that I am free to withdraw and stop participation in the research at any given time. I understand that I am not obliged to answer questions which I prefer not to answer and I can indicate this to the research team.

I will receive a copy of this consent form.

____________________	____________________
Last name	First name
___ / ___ / 2024	____________________
Date (dd/mm/yyyy)	Signature

M.4 Full results

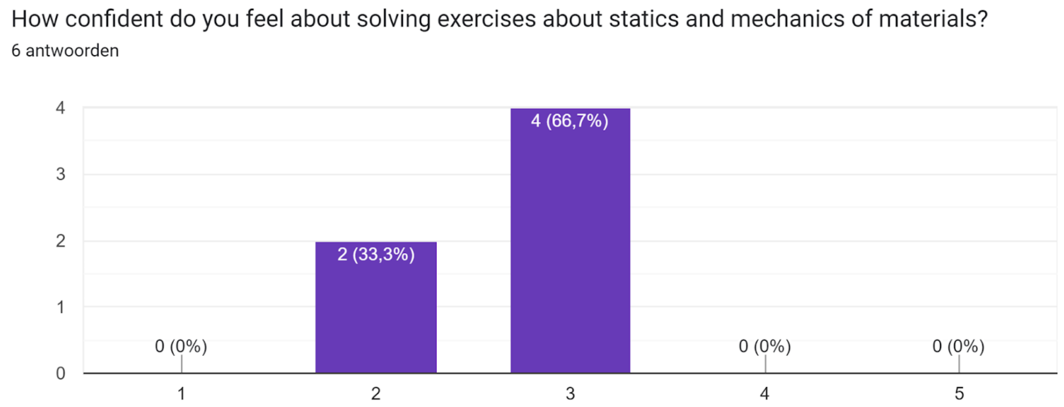
First the observations, secondly the assignment and questionnaire results.

Observed:

1. Most participants first start to read the assignment and manual, some are curious and first check the machine out.
2. The personality of the participants influence the way they perform the test quite heavily. One group was more shy and a little less confident, ending up only testing two samples. The second pair was clearly more extraverted in character and took to work confidently, leading to testing 5 samples. The third pair was also quite confident, however also very precise. This did lead them to a few discoveries of important steps or relevant factors, but also slowed them down a little bit, also testing only two samples.
3. The first pair needed some more stimulation to just go ahead and try things out. Also, when answering the assignment question 9 (what could cause deviations?), they were a bit clueless as to in what direction they needed to think. With a small hint from the researcher they understood they had to think broadly and question every variable and factor.
4. The second pair distinguished themselves by thinking less and doing more, clearly leading to more experimentation. It also lead them to more mistakes and bigger errors between theory and reality, but this is part of the Productive Failure approach. In a real workshop, they would have had more time to improve the measurements. Lastly, this pair asked noticeably more questions to the researcher than the others.
5. In general, the PF theory was visible, for example when the participants learned the deflection formula and noticed that the factors they indicated were almost correct, but not complete or partially wrong. In observation, it was noticeable when the participants had an ‘aha!’-moment.
6. The third pair had the most scientific and structured approach to the problem. They phrased a good objective before starting their measurements: "choosing the lightest sample that bends the least within margins".
7. All groups needed a verbal hint from the researcher to understand that they were supposed to manually move the digital ruler to the deflected position of the beam, so even though this was in the simple user guide, this indicates it was not clear enough.
8. All groups struggled to position the ruler at the correct height, as they had to look directly from the side to align the sample with the correct guideline on the board. None of them realised they could look from the back of the EDA through the transparent board, but when given a hint some tried this out. In general, it is clear this method is not ideal yet.
9. The Excel sheet functioned well as a guide in the process, but as expected, mistakes are easily made. Two pairs both made the mistake of using commas instead of dots for decimal numbers, which Excel does not parse. At the same time, this was also a discovery for them, realising there is a notation difference between English and Dutch. Some participants almost never used the software before.
10. The torque sensor did not play a role in the assignment, but as it was still there in the EDA, the participants all wondered if they needed it. This slightly confusing element actually lead them to think deeper about the situation and what influences bending. Some realised at some point that it did not matter, as it would be the same for each sample. In future iterations, it could be incorporated, for example to see how much torque the joint of the armrest needs to resist.
11. The thinner and the more flexible samples were a hassle to use, as the participants could only apply small loads to them, otherwise the hanger would slide off. However, if the deflection becomes so large that the hanger slides off, the deflection formulas would probably not be valid anymore anyway.
12. During the tests, two out of the three pairs had the realisation that the orientation of the sample can make a difference in how much it bends. In a longer workshop, they could have been stimulated to think why this matters. Consequently, they could have discovered where the stress in a beam is the largest (on the top and bottom).

Assignment and questionnaire:

1. All participants are IDE students.
2. All participants were taking UPE for the first time and are all in their first bachelor year.
    a. One participant studied mechanical engineering for one year, but switched to IDE.
3. The participants felt moderately confident to not very confident about their ability to solve statics and MoM exercises:



4. The students all had a similar problem solving approach, but the order differed. For example:
   “Weigh the lightest sample & move to up to the heaviest. See which bends the least at a set weight.” versus “First discover which material does not bend too much and falls within margins of how much it is allowed to deflect at max. The lightest one from those is the best.”
5. Factors that influence bending as mentioned by the participants:
    a. Length of the beam
    b. Force working on the beam
    c. Shape of the beam
    d. Material of the beam
    e. Distance from load to the fixed point
    f. Stiffness
    g. Thickness
6. What went wrong or was difficult?

a. Reading the height was a bit difficult. Also the weight fell off sometimes.
b. Preventing the weights from falling off was a bit fiddly. And reading / moving to the correct height was hard to see
c. Reading the length of the beams was not super accurate just like moving the deflection ruler. And sometimes it was difficult that the weights were moving. Also the piece in which you fixed the beam was not very stable
d. Finding out what to do and how to do it
e. Setting the deflection ruler and reading it was difficult, you easily make mistakes
f. Setting up the deflection ruler was difficult because not all beams reached up to the end and therefore had to be measured from 25cm (which was not the free end of the beam)

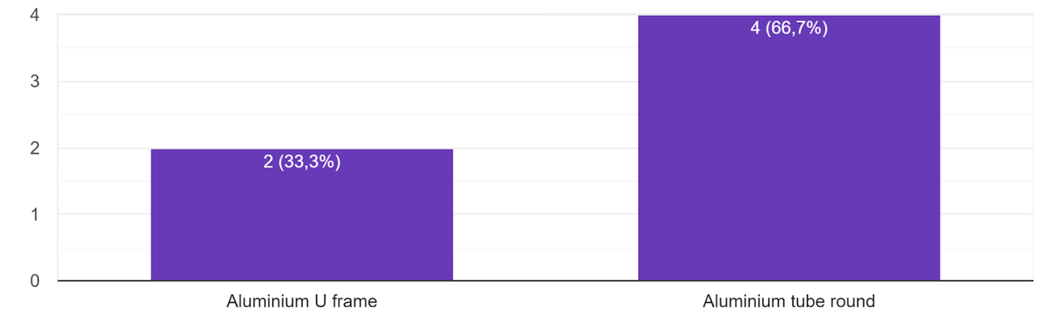
7. Participants reflection on the factors they indicated and correspondence with formula:

Were the factors you indicated before you knew the equation correct? If not, what was the difference?
6 antwoorden

8. The participants now started calculating, measuring and comparing. Their reflection on the accuracy:
   a. Pretty okay, 8mm theoretical, 12mm in real life for alu tube. But with the alu L profile this was quite different, 5mm vs 12mm, probably due to a difference in orientation when fixing it.
   b. 1. There is a difference between measured (12.55) and calculated (8.05). 2. Here is also a difference, 12.05 vs calculated 5.64. So both have a difference but not extremely large.
   c. They were not corresponding very well
   d. They did not correspond well with the measurements
   e. The 2 different values weren't right, but it was right that the aluminium U profile had less deflection than the aluminium rod rectangle horizontal, we also measured this.
   f. The values did not correspond, but the ratio between the two measurements was quite correct.
9. Possible explanations for deviations given by the participants:
   a. Orientation, material not perfect (different E modulus), dimensions not perfect (different Moment of Inertia), play in the device, reading mistakes
   b. With the L shaped aluminium it's possible the difference is caused by the way of measuring: the corner to the left or to the top gives different measurements. It is also possible that the material is damaged or not 100% pure. Lastly it might be due to reading errors

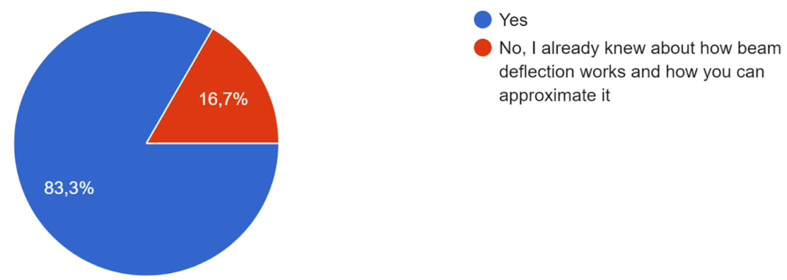
   c. Inaccuracies during measuring
   d. Mistakes in the execution of the test. Mistakes in taking measurements.
   e. Measuring errors like reading the deflection ruler wrong and the accuracy of the sample's values
   f. Mistakes in reading of the measurements and the accuracy of the given values in Excel in comparison to the actual beam samples
10. Choice of sample ("solution" to the given assignment):

What sample would you choose to design the armrest with?
6 antwoorden



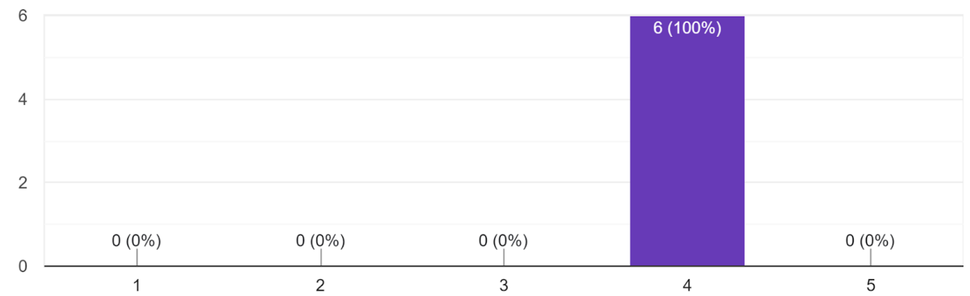
11. Wrap-up:

Did you learning anything new today?
6 antwoorden



12.

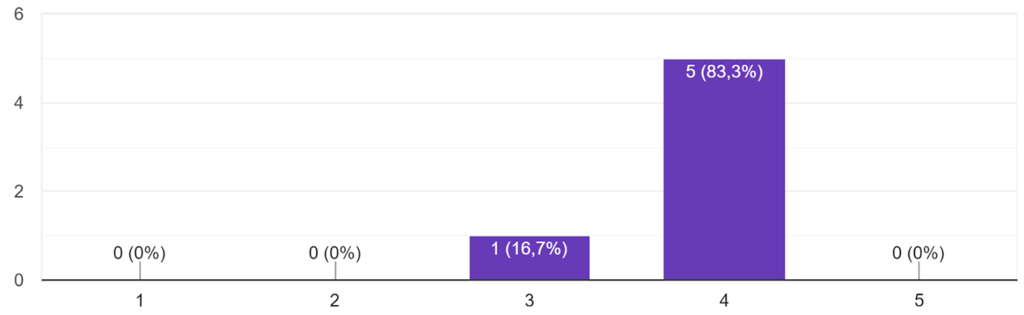
How much did you enjoy using the experiential machine in the workshop?
6 antwoorden



13.

How easy was it to use the EDA with two people?

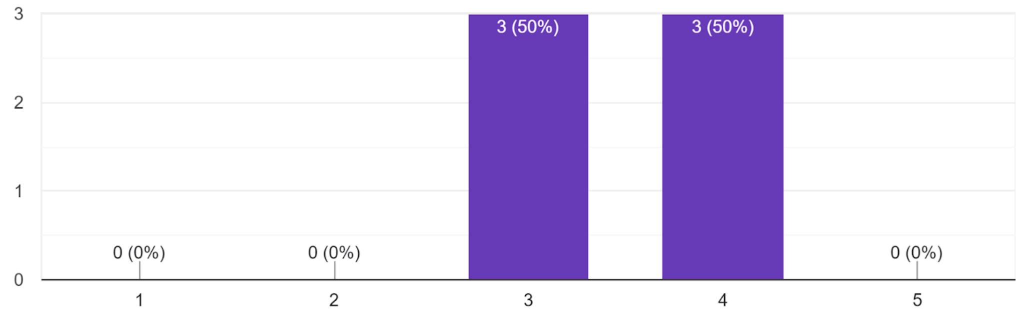
6 antwoorden



14.

How confident do you feel about what you learned?

6 antwoorden



15. Was there a moment during the test in which you felt lost and did not know what to do?
    a. Not really, but it's helpful if you have someone there to ask questions, because we did have a few.
    b. In the beginning it took some figuring out to know how everything worked which was a bit difficult, but afterwards it was quite simple to use
    c. When P4 and I discovered that our measurements and calculations were totally not corresponding
    d. At the start for a little bit
    e. Yes, in the beginning I found it hard to the EDA exactly worked, but at a certain point I understood it after trying a few times.
    f. Not really, the moments we got stuck it was clear how to solve this
16. None of the participants experienced any physical discomfort.
17. None of the participants remembered the formula 100% correct, but 5 out of 6 had at least the correct variables and 4 out of 6 had a correct structure.

Appendix N. Cost

Part name	Quantity		€/piece	Total
Aluminium extrusions	2.81	m	20	€ 56.20
Connector parts				
Corner pieces	10	pc	1	€ 10.00
Nuts and bolts	50	pc	0.1	€ 5.00
Ready parts				
Torque sensor	1	pc	59.99	€ 59.99
Digital ruler	1	pc	37.98	€ 37.98
Hanger with weights	1	pc	20	€ 20.00
Custom parts				
Guiding board acrylic (laser cut) incl. machine costs	1	pc	17.5	€ 17.50
Storage compartments (laser cut) incl. machine costs	2	pc	6.25	€ 12.50
Modified torque wrench bits	2	pc	1	€ 2.00
Beam samples	10	pc	0.5	€ 5.00
Tools and accessories				
Hex key	3	pc	1	€ 3.00
Ruler 30cm	1	pc	1	€ 1.00
Screwdriver	1	pc	2	€ 2.00
Hoseclamps	3	pc	0.5	€ 1.50
				€ 233.67
Labour costs	3	hr	20	€ 60.00
			+	€ 293.67

Appendix O. Reflection

Using the ELT as a reflective method, we have 4 stages (Institute for Experiential Learning, 2023):
1. Experiencing (Concrete Experience): Learning begins when a learner uses senses and perceptions to engage in what is happening now.
2. Reflecting (Reflective Observation): After the experience, a learner reflects on what happened and connects feelings with ideas about the experience.
3. Thinking (Abstract Conceptualization): The learner engages in thinking to reach conclusions and form theories, concepts, or general principles that can be tested
4. Acting (Active Experimentation): The learner tests the theory and applies what was learned to get feedback and create the next experience.

With these four stages I reflected on two main situations that I experienced during this project. The first is about my initial green light meeting, which we then turned in a back-from-holiday meeting as there was quite a lot of feedback from my supervisors still. The second is about a recurring experience that I have in project where I work on my own, where I underestimate my own work.

Subject 1: Green light feedback

1. Experiencing: I presented my first green light meeting thinking my work up to that point would be sufficient to continue. However, I got feedback from my supervisors that there was an important part of argumentation missing in my thesis. It felt slightly disappointing but also fair, as I realised what they meant. The feedback also included the need for showing design methodology more in my report. I was a little bit overwhelmed by it, but in this case I had already realised before that I was not actively naming methods. It however felt like I would be faking that I used methods if I added this in hindsight.

2. Reflecting: So why did this happen? First of all, I made a conscious decision of focusing more on embodiment in my report as I thought the end result would be the most important, and showing the process I went through would be largely redundant. Secondly, there was a period in the beginning of summer where the contact between me and my supervisors was less frequent. I decided to press on with my report and submit it, but this approach meant they didn't have the opportunity to provide feedback and help adjust the direction of my work before my green light anymore.
   Moreover, I didn't explicitly include methods in my report because I was using them subconsciously, which is something designers often do, according to Stefan. Personally, I tend to be more of a go-with-the-flow person and don't naturally rely on formal methods, even though they can be valuable.

3. Thinking: Now, what can I improve? The main thing that I could have done differently is reach out to Wilfred and Stefan earlier in the process. This way I would have given myself the chance to improve and understand the final goal of the thesis better. It would also have saved me 2-3 weeks on the total project, as I now had to correct quite a lot after my initial green light meeting. I could have also consulted more thesis reports by other students to learn from their experience. I did actually do this, but I used the thesis about the LETT, which is maybe not the best example as it had a very concrete assignment (design a desktop sized tensile tester). In my thesis, the problem space was really quite large which asked for extensive exploration. Considering the methodology, I could have reviewed the rubric for graduation projects to realise I should include some references to this.

4. Acting: To improve my thesis during the last phase of the project (including two extra weeks I received for a new green light meeting), I decided to stay in closer contact with my supervisors. The first thing I did a week after the initial green light was presenting my new report structure, and with their approval I began making the necessary revisions.
   In this case, I had to add the references to design methodology like from the DDG in hindsight, but that actually turned out to be not as difficult or "faking it" as I thought. For example, I read the chapter Product usability evaluation and it describes that test results become more valid the more tests you perform. Even though I did a small test, I already experienced this, as I became more confident with every test I conducted. My own ever so slight insecurity with the first one also influences the participant.

Subject 2: Underestimating own work

1. Experiencing: During the project there were a few moments where I started to become a little bit insecure about my progress and results. This for example happened in the beginning when Robin started prototyping really quickly while I was still absorbing the problem space and identifying the relevant factors. The insecurity makes me feel unmotivated sometimes. It also happened later in the project when I realised I was not going to be able to deliver a production and deployment ready design. This felt like it was insufficient.

2. Reflecting: This happens first of all when I compare myself to others, and secondly when I have not taken a step back and zoomed out to see the bigger picture. Working on my own on a project is not one of my strengths, I am a cooperator by nature. This is also why I felt insecure: I was underestimating my own work.

3. Thinking: So how can I overcome this? I could have talked more with other students sooner. This way I would get an opinion outside of my own perspective. Fellow students also always approach this with a positive mindset and their feedback is constructive and in your own "language" as they often find themselves in the same situations.

4. Acting: In the future I will keep in mind that when I work on something on my own, I should not forget to take a step back now and then, do something else or ask someone's opinion. At some point Bas Flipsen (UPE coordinator and co-client with Stefan) came by to get an update on what I was doing, after we did not have contact for quite a while. When I showed him the the prototype and explained, he then summarised it in a constructive and enthusiastic way. This gave me a motivational boost. Another positive experience I had during this project was when I was testing the EDA with first year students, and one asked about my project. They assumed the prototype was made by the staff and given to me to test with them. When I said I made it myself that student said "oh wow, cool!". That made me reflect on all the work I have done.

Learning is a cycle. Therefore the examples I gave in this reflection are not finite, and will lead to new experiencing in the future in which I will encounter the same situations. In these situations I will apply what I learned during this project, learn new things and apply those again and again.


EDA
9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30