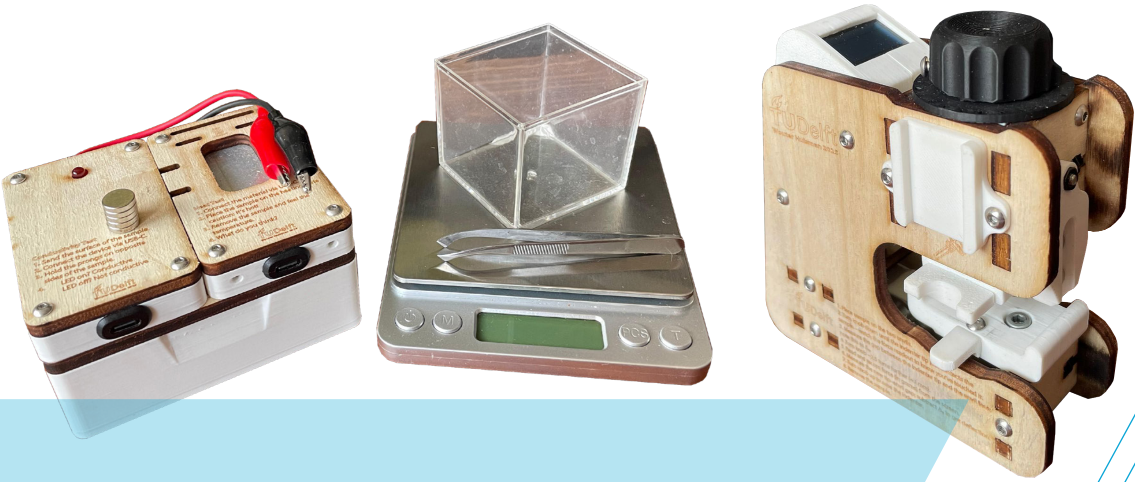
Msc. Graduation Thesis

Experiential Material Determination Station



Wouter Huisman

TU Delft

Msc Graduation Thesis
Delft, June 2025

Author
Msc. Integrated Product Design
5596777

Project Chair
Dr. Ir. Erik Tempelman
Associate Professor | Sustainable Design Engineering

Project Mentor
Ing. Adrie Kooijman

Client
Dr. Ir. S.F.J. (Bas) Flipsen

TU Delft

Delft University of Technology
Faculty of Industrial Design Engineering

Landbergstraat 15, 2628 CE Delft

Preface

This thesis is the result of my MSc graduation project at the Faculty of Industrial Design Engineering.

I've always been drawn to the technical side of IDE, the part where design turns into something you can build, test, and reason through. Whether it's prototyping, engineering details, or making something work that didn't before, that's where I feel at home. This project allowed me to fully lean into that mindset.

With a more practical background, the transition into the master's programme took some adjustment. The process here focused less on making and more on questioning, digging into what the real problem is before jumping to solutions. That took some getting used to, but it changed the way I think about design engineering. It taught me that building something is more satisfying when you know exactly why it should exist. This project gave me the time and space to iterate properly, work independently, and finish with something I fully stand behind.

I would like to thank my graduation supervisor, Erik Tempelman, for his unwavering enthusiasm, commitment, and availability, and for always seeming to know something interesting about topics I didn't even know I cared about. I also want to thank my mentor, Adrie Kooijman, for his critical perspective, extensive knowledge of the subject, and our many insightful (and often philosophical) conversations that left me heading home with yet another life lesson.

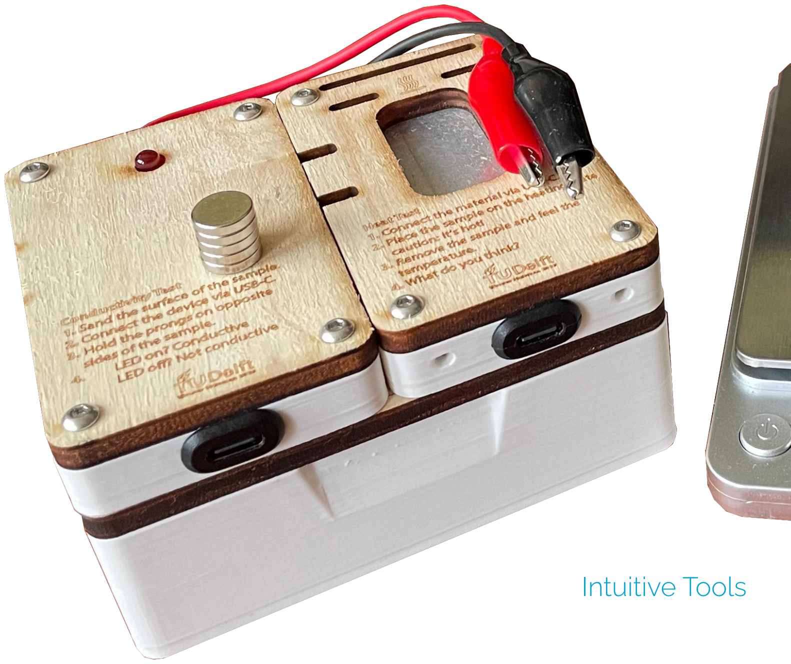
I'm deeply grateful to my parents and friends for their support throughout this project, and in particular to my partner, *Fleur Leemburg*, for being there in every way that matters.

This project has truly felt like an accomplishment. I hope you enjoy reading as much as I enjoyed building.

Though honestly, I doubt that's possible.

Wouter Huisman
Delft, June 2025

Executive Summary



Intuitive Tools

Context and Original Assignment

This graduation project was carried out within the Understanding Product Engineering (UPE) course at TU Delft. In this course, first-year students are introduced to material properties and their role in design decisions. While theoretical knowledge is well-covered, students rarely get the chance to test or interact with materials physically. This issue is only growing, as educators face increasing group sizes and shrinking budgets, making hands-on teaching harder to organise, especially in light of recent government funding cuts. As a result, key concepts like stiffness often remain abstract and hard to apply in practice.

The original brief focused on developing low-tech tools to help students identify unknown materials through sensory-based testing. The aim was to support material intuition and bridge the gap between theory and hands-on experience. This project builds on that idea but shifts the focus toward a solution that allows students to engage with materials independently and in small groups, without requiring constant supervision or lab infrastructure.

Redefining the Brief

Early analysis of the course structure, combined with feedback from user tests, revealed a deeper issue. Students didn't just struggle to name materials, they struggled to reason about material behaviour in a structured way. Concepts like stiffness and deformation were introduced in lectures but never reinforced through measurement or experimentation.

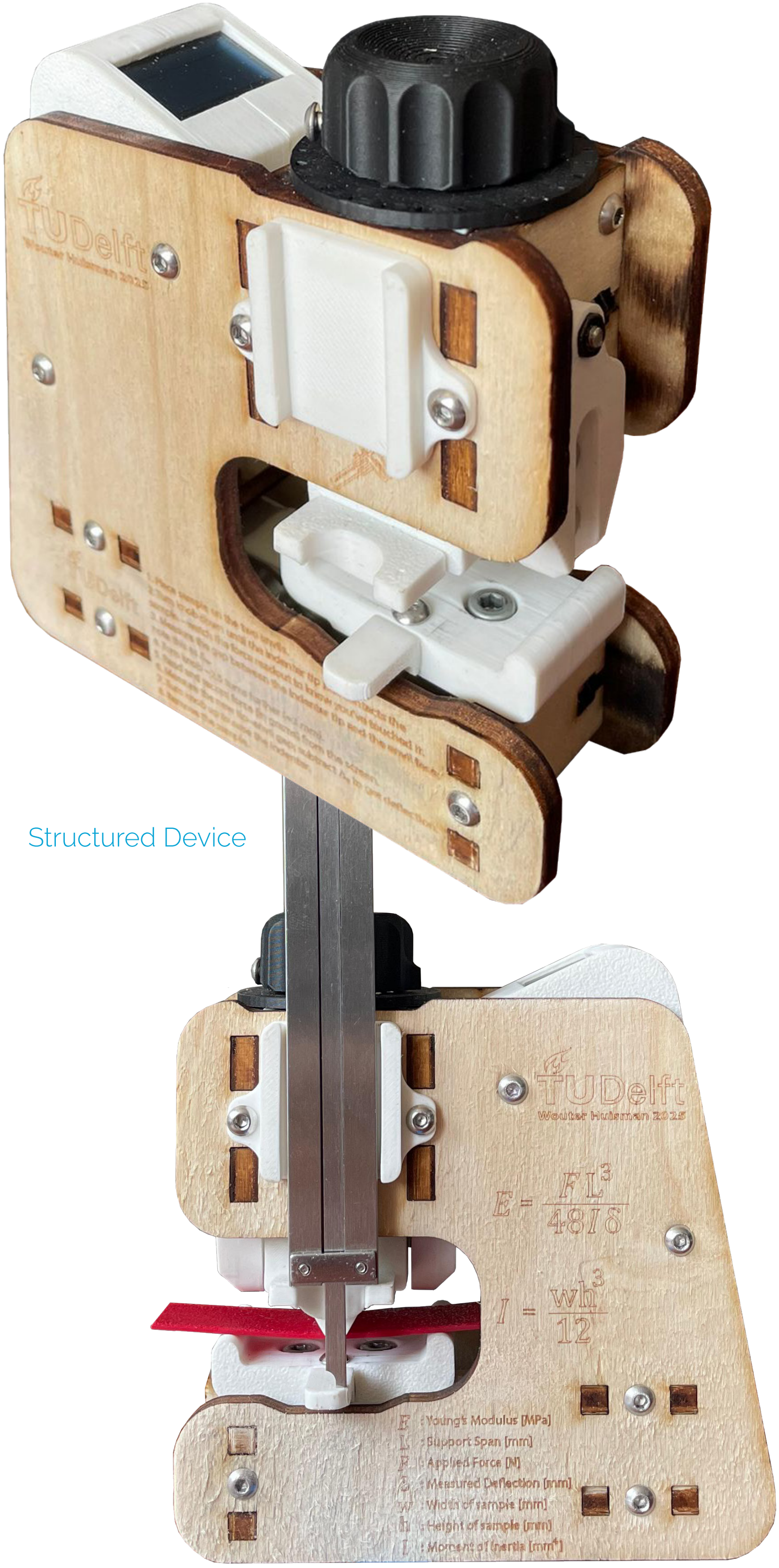
One key insight was that scientific measurement itself was missing from the course. Students had no experience dealing with real data, uncertainty, or variability, all essential aspects of engineering reasoning. As a result, the brief was redefined to focus on helping students not just explore materials but analyse them. The new goal became to support the development of both intuitive understanding and structured interpretation of material stiffness.

Final Setup

The final result is a single setup with two sides, each designed to support a different stage of learning. On one side, students interact with a set of intuitive tools that let them explore basic material properties such as hardness, density, and magnetism through hands-on trial. These tools are intended to trigger curiosity, encourage early reasoning, and help students confront their assumptions about materials.

On the other side, the structured component invites students to dive deeper. Using a compact three-point bending setup, they measure force and deflection, calculate an effective modulus, and discover that theory alone doesn't always match what materials do in practice. The numbers seen in theory assignments or exams don't always hold up when real materials introduce variation, uncertainty, or unexpected behaviour, and that experience is central to the learning goal.

The setup is built from a combination of laser-cut wooden parts, 3D-printed components, and affordable off-the-shelf electronics. All parts are easy to produce and assemble, making the design scalable for classroom use without specialised equipment or supervision.



Structured Device

Why It Works

The setup was tested in two classroom workshops designed around the Productive Failure approach. In the first session, students explored materials informally using the intuitive tools. In the second, they worked with the structured bending setup to measure and calculate stiffness. This sequence encouraged students to confront their assumptions, make early observations, and later connect those to theoretical concepts through data and analysis. This setup gave students the opportunity to engage with measurement in a way that theory alone doesn't offer. During the workshops, they were confronted with questions like when to take a reading, how much force to apply, and how to interpret variation in the. This shift from open-ended exploration to measured analysis aligns with the course's intention to build both intuitive and structured understanding of material behaviour.'

Mechanically, the setup performs reliably. A full uncertainty calculation based on measurement variation placed the total error margin at ±11.3%. To verify this, a series of repeated tests was performed using four different materials. The standard deviation across trials was approximately 6%, confirming that the setup produces consistent and usable results under realistic classroom conditions.

Looking Ahead

The setup is ready for implementation in the UPE course. Small improvements to instructional clarity and sensor mounting are recommended before full rollout. There is interest to test the setup in the official course structure, and there is potential for broader use in other educational contexts where hands-on material testing is relevant.

Table of Contents

1. Project Introduction

1.1 Introduction

In design education, it's important that students understand how material properties affect things like performance, durability, and safety. This is especially true in early courses like Understanding Product Engineering (UPE) at the Industrial Design Engineering (IDE) faculty at the TU Delft, where students first get exposed to material behaviour, physics, and production techniques.

A lot of that is taught through lectures or tools like Granta EduPack, a materials database (Ansys Inc., 2023), but actual hands-on experience with materials is pretty limited. That's partly because of safety and staff limitations, but also just the reality of how education is shifting in the Netherlands. Budget cuts (Universiteit Leiden, 2025; DutchNews.nl, 2025) and more students per educator (OECD, 2023) make it harder to offer lab-heavy teaching, which means students often miss the chance to actually test or explore real materials during their studies.

Course coordinator, sBas Flipsen, sees this as a gap. There's a clear need for something low-cost and practical, a setup students can use on their own, to get a feel for how materials behave, without needing full lab access or constant supervision.

My Own experience

From my own time in the course, I noticed how abstract this stuff can feel. I've seen people struggle to understand the difference between stiffness and hardness, or how to read a force–deflection curve if they've never actually felt a material bend. It's not that we don't care, we just haven't seen it in action. Meanwhile, tools like 3D printers or laser cutters are used all the time. That's partly because they're easy to use, but also because you immediately see what happens. If we want students to build the same kind of confidence with material properties, the testing setup needs to offer the same kind of direct, hands-on feedback. That's what this project is trying to improve.

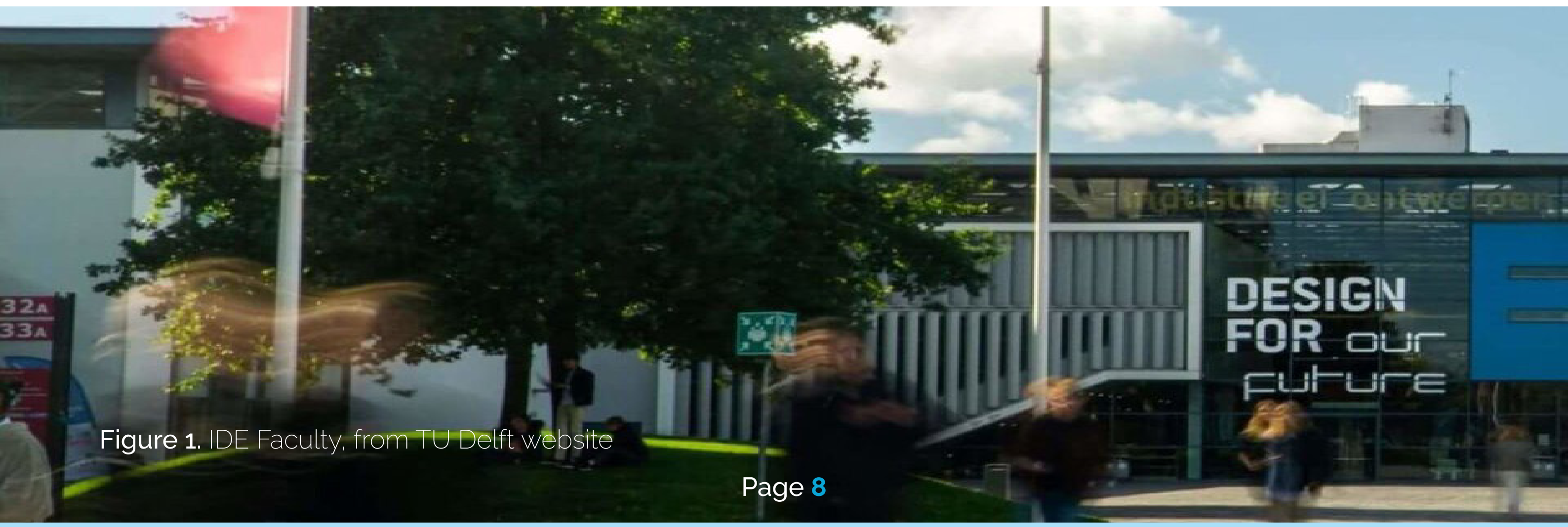


Figure 1. IDE Faculty, from TU Delft website

1.2 Assignment

This project focusses on the UPE course at TU Delft and focuses on improving how students engage with and understand material properties. While the theory is well-covered, physical interaction with materials is limited, leaving a gap between what students learn and what they experience. This project explores how that gap can be closed through practical, scalable testing tools.

1.2.1 Background

The original assignment (*Appendix A*) aimed to help students identify unknown materials using multiple low-tech tests, supported by Granta EduPack. This was meant to build material intuition through hands-on interaction.

However, early research and curriculum analysis revealed a deeper issue: students weren't just struggling to name materials, they were struggling to understand what those materials actually do. The brief was therefore refined to focus not on identification, but on helping students interpret and reason about material behaviour.

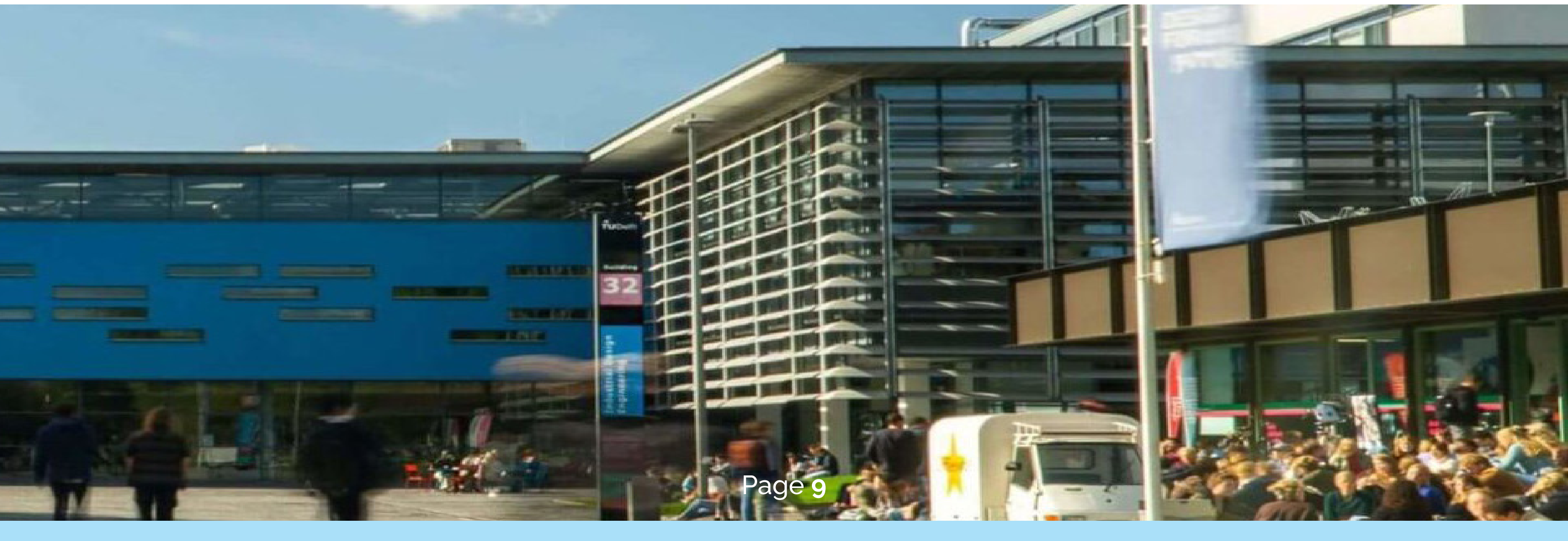
1.2.2 Research Questions

To guide the direction of the project and clarify what the setup needed to achieve, three research questions were used:

1. **How do different types of hands-on testing experiences support student learning about materials?** It's important to understand what kind of interaction helps students not just engage with materials but also develop useful and accurate mental models of material behaviour.
2. **How well does the current UPE course align theory, practice, and assessment in material education?** Identifying gaps between what students are taught, what they do, and what they're tested on helps ensure that the setup contributes meaningfully to the course.
3. **What practical and educational constraints shape the design of a classroom-ready testing setup?** To be realistically implemented, the setup must fit within real classroom conditions including safety, budget, group size, and supervision limits.

1.2.3 Goal of the Assignment

The goal of this project is to design and validate a classroom-ready testing setup that helps students build a deeper understanding of material properties through hands-on experience. The aim is to show how different forms of material testing can be combined into a setup that supports learning, works within course constraints, and scales beyond a single prototype. The final result will be a validated setup, tested with students, and ready for integration into the UPE course, with potential application in other design education contexts.



1.3 Method and Approach

The project followed a research-through-design approach, developed through an iterative process (Figure 2) and inspired by the Double Diamond model (Figure 3), alternating between open exploration and focused refinement. The method was mainly shaped by what the context and design process required at each stage. The structure of this report reflects the development of the solution step by step, from early analysis to final validation.

1.3.1 Analysis Phase (Discover)

The process started with a broad technical exploration: investigating which material properties could be tested safely and meaningfully in an educational setting, and what kind of test methods might support that. This included looking at properties like stiffness, hardness, magnetism, and conductivity. After that, the focus shifted toward a more contextual analysis of the UPE course itself: what the learning goals were, how materials were currently being taught, and where theory, practice, and assessment weren't lining up. Together, these two perspectives helped refine the original design brief (Appendix A) and define what the setup needed to do.

1.3.2 Concept Development (Define to early Develop)

From the combined analysis, two learning tracks emerged: one focused on intuitive, hands-on exploration, and one focused on structured, measurable testing. Although both were explored in parallel, the structured track became the focus of the design work. It aligned most closely with the gaps identified in the course, especially the need for repeatable, analytical reasoning around material properties. The intuitive track was developed in the background, following the same iterative process, but required less technical development, being based on current curriculum activities. It would return in the final design as part of a combined setup.

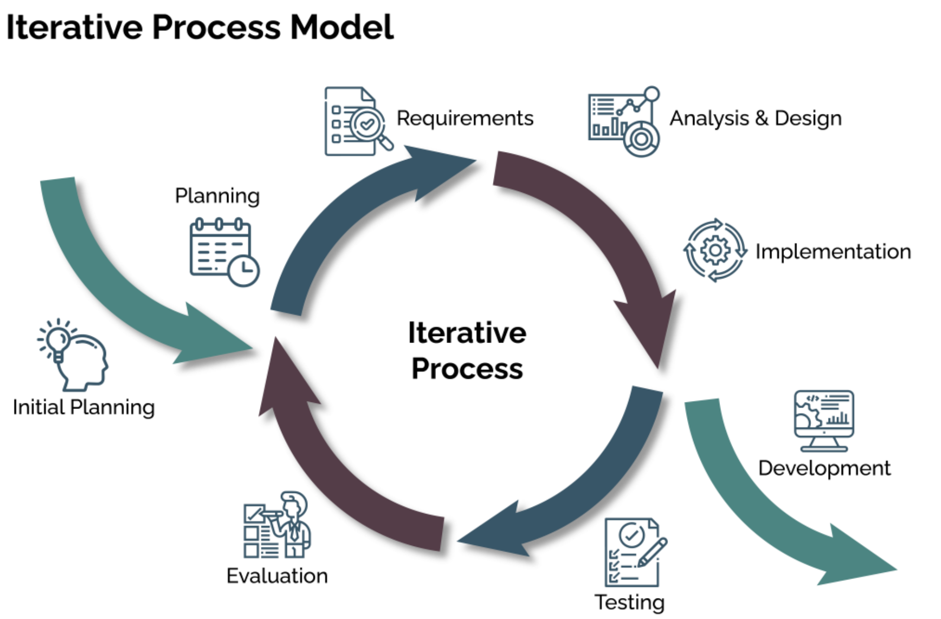


Figure 2. Iterative Process Model (Radiant Digital, n.d.)

1.3.3 Prototype Testing (Develop)

A working prototype of the structured setup was built and tested with students. The goal was to see if it actually helped them understand stiffness and material behaviour, and whether the measurements were consistent enough for classroom use. Alongside user testing, some basic mechanical evaluation was done to assess force stability, repeatability, and ease of use. Feedback from students and technical results were used to guide the next phase.

1.3.4 Iteration Phase (Develop to Deliver)

Based on the feedback, the design was refined and rebuilt. The goal here was to make sure the setup could be used independently by students in the classroom, while still working reliably both mechanically and educationally. Improvements were made to the force input, measurement feedback, and sample alignment, and small details were added to support correct usage without supervision.

1.3.5 Final Design Integration (Deliver)

After the design iteration, the final version of the structured setup was completed. At this point, the intuitive tools were brought back in and integrated into a full two-part classroom setup. A supporting workshop format was designed around the structured setup, using a Productive Failure approach: students first explore and try to solve a task on their own, before theory is introduced to help make sense of what they experienced. This helped structure the role of the tool within the course and ensured that it supported both exploration and reflection.

1.3.6 Validation and Implementation

To validate the final setup, two workshops were run with students. One focused on open material exploration, the other on stiffness testing and load prediction using the device. Observations and student feedback showed that the setup helped students shift from vague assumptions to more structured reasoning. In parallel, mechanical tests confirmed that the setup could deliver repeatable data within acceptable uncertainty for educational use. Both sides of validation pointed toward successful integration in the UPE course.

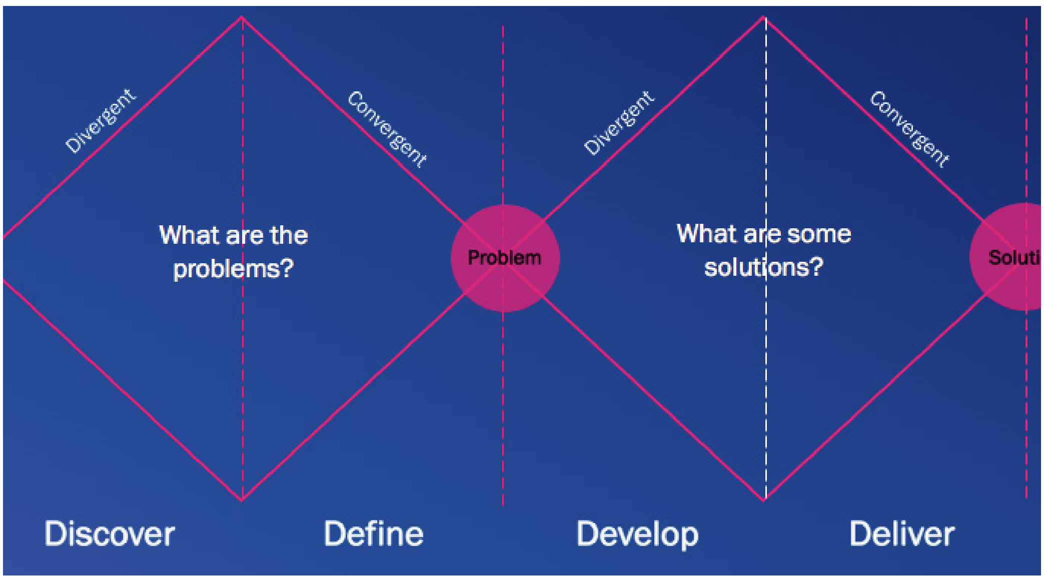


Figure 3. Double Diamond Model (Delft University of Technology, n.d.)

2. Exploratory Analysis

2.1 Technical Exploration

The project began on the assumption that students could learn more about material properties by identifying unknown materials through direct, hands-on testing. This assumption introduced a general question into different materials, their properties, and how a person could test them in an educational setting.

2.1.1 Material Selection

The goal of the material selection was to create a shortlist that would reflect real-world product applications and offer meaningful differences in behaviour and properties for students to experience. Three criteria were used:

1. **Relevance to Product Design**: Materials had to represent those commonly encountered in industrial design applications.
2. **Accessibility and Safety**: Materials had to be safe to handle and readily available in usable quantities for use in class.
3. **Diversity**: A range of different material types was considered to expose students to varying mechanical and physical behaviours.

Categories explored included polymers, metals, natural materials such as wood and bamboo, and two additional materials: a composite (Carbon Fiber Reinforced Plastic, CFRP) and a ceramic (soda-lime glass). A full overview the shortlist of materials, and their selection reasoning can be found in Appendix B1.

2.1.2 Sample Form Exploration

The form in which materials were tested was recognized as important for both educational value and experimental reliability. Two primary approaches were considered:

- **Product pieces**: Real-life pieces to emphasize everyday, situational relevance, even if there would necessarily be some variation.
- **Standardized Material Strips:** Standardized samples made for uniform, similar results, albeit possibly further from students' experience.

Either one can be useful, so both sample forms were kept in mind for future inclusion, pending the test procedure and learning goals

2.1.3 Property and Testing Method Selection

The material properties focus on safety, feasibility of independent testing by students and their relevance to engineering decisions. The properties that were considered included (full list with considerations in Appendix B2):

- Density
- Hardness
- Fracture Toughness
- Young's Modulus
- Electrical resistivity
- Magnetism.

Hands-on methods were chosen to help students connect theory with practice, avoiding "black box" tools that hide what's going on. The tests included familiar techniques like the Archimedes density test, Scratch and Vickers hardness tests, 3-point bending, magnetic checks, and basic resistivity measurements.

Figure 4. Destructive Testing - Tensile Test, Source: MFE Inspection Solutions (2024)

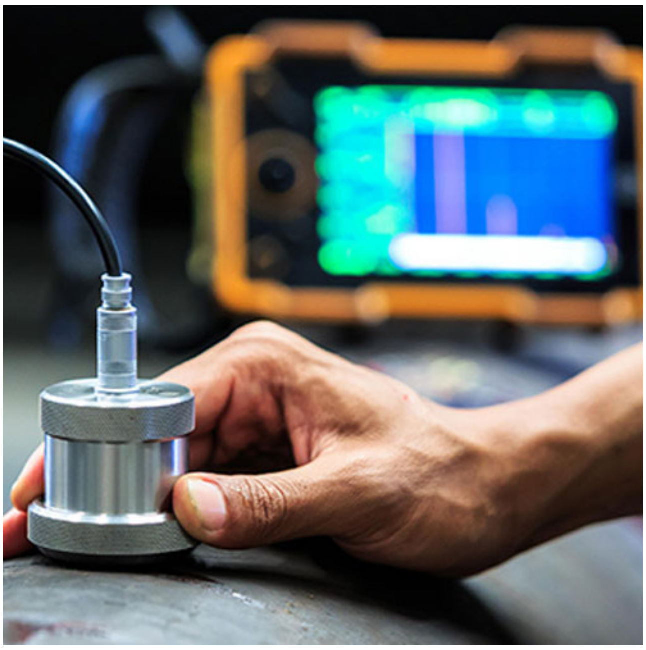


Figure 5. Non-Destructive Testing - Ultrasonic Testing. Source: Format NDT (n.d.)

Each method was labelled as destructive (Figure 4) or non-destructive (Figure 5), meaning if the test permanently damages the tested sample (Beitz, Küttner, & Heisel, 2010), balancing learning value with safety, reuse, and how complex the setup was. The full list with considerations can be found in Appendix B3.

2.2 Course Coordinator Input

Early conversations with the course coordinator highlighted several practical challenges within the project. One major issue was setup time. Existing equipment often takes too long to set up and clean up, which cuts into valuable workshop hours and frustrates instructors. Portability and storage were also raised as significant concerns. Moving a bulky setup between classrooms is difficult, and limited storage space means any new setup must be compact and easy to pack away.
Safety emerged as another key priority. The device needs to be safe enough for students to use independently, without constant supervision. Lastly, cost and ease of construction were named. Given the size of the course and budget constraints, the setup must be affordable, straightforward to build, and maintainable without specialized tools or complicated assembly.

2.2.1 Safety Considerations

The IDE Faculty's Low-End Tensile Tester (LETT) project (Figure 6) showed that with the right design choices, like adding enclosures or limiting how much force is used, it's possible to build a safe, self-contained setup. But previous experience with projects in this course highlighted the importance of addressing safety early on. An earlier thesis project for the UPE course (Taen, 2024) was unable to be implemented due to safety certification issues, underscoring the need for a proper safety approach. A structured approach was developed by logically considering three levels: materials, properties, and methods. This framework helped guide the exploration of potential risks and informed subsequent design choices.

- Materials: only materials that are safe to handle and unlikely to shatter dangerously were selected. Materials with toxic, reactive, or flammable properties were excluded entirely.
- Properties: tests requiring hazardous procedures, such as melting point or corrosion resistance, were excluded from the testing programme.
- Methods: testing setups were chosen or adapted to reduce risks. (e.g. by limiting the applied forces and adding enclosures where necessary. Clear user instructions were developed to support safe, independent use by students.

2.2.2 Portability and Setup Time

Portability and storage constraints require the setup to be flexible enough to move between classrooms and compact enough for limited storage spaces, especially as tools are shared. Three key requirements emerged from discussions: the setup must be quick to setup, flexible and portable.

2.2.3 Ease of construction and accessibility

The setup also needed to be easy to build and use. This requirement emerged from discussions with the course coordinator and a review of existing educational tools. It was designed to be constructed from common parts and simple tools to ensure it could be assembled not only at TU Delft but also in schools and maker spaces. The goal was to keep the design affordable, sturdy, and straightforward without requiring specialized skills. At the same time, there needed to be a balance between portability and maintaining stability and safety during use.

2.2.4 Cost

Given the size of the UPE course (approximately 300 students), discussions with the course coordinator led to the decision to divide the workshops into two timeslots, with students sharing a single setup. This approach reduces the number of required units to about 75. To ensure feasibility within the course budget, a target production cost of €50 per setup was established.

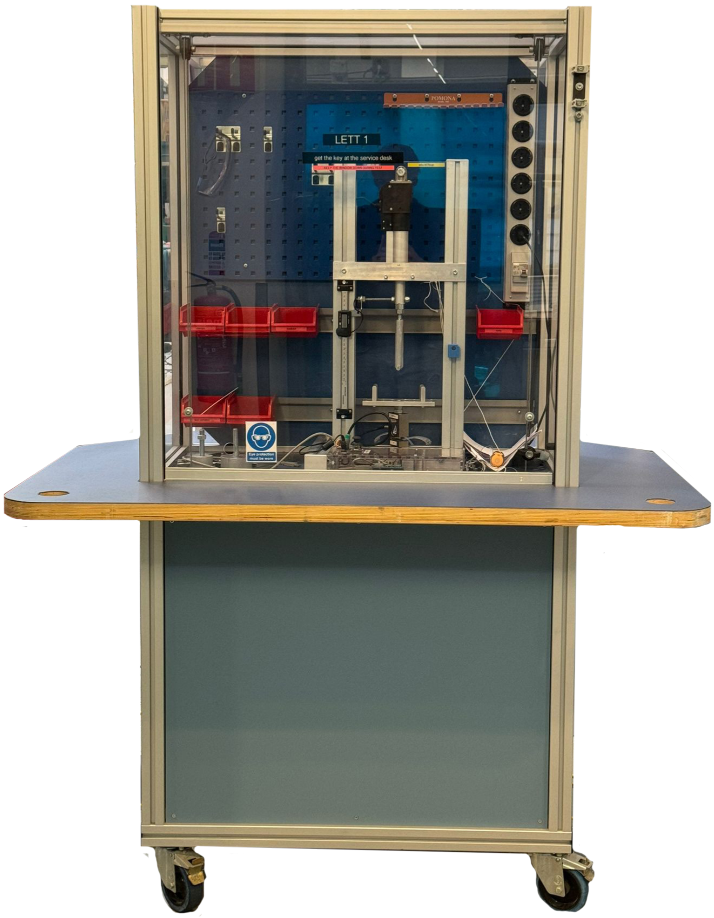


Figure 6. The TU Delft LETT, A low-cost, safe, and self-contained device designed for independent student use in material testing education. The setup demonstrates tensile behaviour in materials but is limited by availability and automation of force input and deflection measurement.

2.3 Stakeholders

This project involves multiple stakeholders. The setup is designed primarily for students but must also work within the needs and constraints of teaching staff and faculty-level goals.

Primary Stakeholders

- Students: Students are the main users of the setup, so it needs to feel clear and hands-on. If the tools are easy to work with and show material behaviour in a direct way, it becomes much easier to connect theory to what's actually happening in practice. The goal is to support independent learning without making things overly complicated.
- UPE Course Coordinator: The coordinator deals with big groups and limited time. A setup that requires minimal explanation, support and supervision cuts down on how much supervision is needed. That helps keep workshops running smoothly while still meeting the course's learning goals.
- Faculty of Industrial Design Engineering (IDE): The faculty benefits from tools that can be reused across different courses and teaching styles. If the setup is scalable and flexible, it fits with IDE's broader aim to blend theory with applied, practical learning.

Secondary Stakeholders

- Other Faculties: Departments like Mechanical or Civil Engineering may adopt similar setups for material education, especially where hands-on learning is needed without full lab facilities.
- TU Delft: At the institutional level, the project supports TU Delft's ambition to innovate education and promote independent learning, especially when scalable, affordable tools can be reused across disciplines.
- Other Educational Institutions: Because the setup is low-cost, safe, and independent, it could also be applied in secondary schools, technical colleges, or other universities looking to make material behaviour more accessible to students.

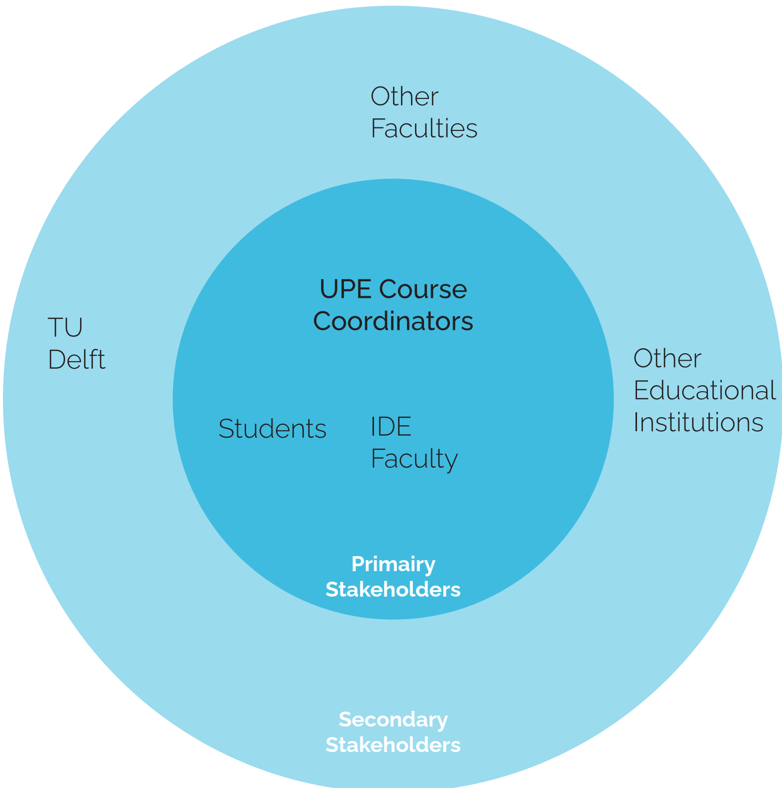


Figure 7 Stakeholder Map

2.4 Educational Exploration

This project builds partly on prior research carried out by Robin Taen (2024), which explored the challenges faced by students within the Faculty of Industrial Design Engineering at TU Delft, particularly in the UPE course. His research focused on how engineering concepts such as material behaviour, manufacturing processes, and abstract topics like Normal and Vertical Moment (NVM) lines were understood and applied by students.

The findings highlighted the importance of experiential learning to improve conceptual understanding and retention. However, they also pointed out that simply providing hands-on activities was not enough: students often needed structured feedback and guidance to correctly interpret what they experienced.

His research also created insights into other setups at the faculty. One example is the Low-End Tensile Tester (LETT). It works well in terms of safety and independence, but student feedback showed a few problems. The setup wasn't always easy to use, and in group settings, usually just one person did the testing while the others watched. That made it harder to keep everyone involved.
The main insights drawn from this prior research and experience are:

- Barriers to Hands-On Learning: Setups need to be easily accessible and intuitive. Otherwise, students tend to avoid them in favour of simpler tools like 3D printers or laser cutters.
- Importance of Experiential Learning: Active engagement helps students better understand material behaviour, but structured feedback is crucial to avoid misinterpretations.
- Role of Accessibility and Context: Setups must be easy to use, portable, and available without heavy supervision to promote genuine independent learning.
- Challenges in Group Work: Group-based setups often lead to passive participation, reducing the effectiveness of experiential learning activities.
- Mismatch Between Learning Objectives and Teaching Activities: The research showed gaps between the desired learning outcomes and the actual activities and assessments, highlighting the need for better alignment.
- Potential Scalability: If designed with flexibility in mind, a modular setup could be used beyond UPE. Courses like Product Engineering (PE), Materials & Manufacturing (M&M), and Advanced Prototyping (AP) could also benefit, though each would need slightly different tools or levels of depth.

A key theme that stood out was the gap between how students explored materials through instinct and how they were expected to evaluate them in a more structured, analytical way. Hands-on tools were clearly valued, students engaged with them, and they helped make abstract properties feel more real. But at the same time, those tools don't always support the kind of consistent, measurable analysis needed for engineering tasks.
These findings helped shape the early setup. The goal was to find a balance, keeping things hands-on and intuitive, while still making sure the tests supported proper analysis and clear structured interpretation.

2.5 User Testing

To explore this value of intuitive versus structured testing, eleven IDE students tested two methods for assessing material hardness: a simple scratch test and a more structured simplified Vickers test. Each participant performed both tests using the same material samples, followed by a short reflection. The goal was to compare how these approaches supported student understanding, and how preferences, confidence, and learning outcomes differed between them. The full test setup, anonymised responses and the full study can be found in Appendix C

Conclusions

The test highlighted a clear trade-off between ease of use and reliability. Students generally found the intuitive test easier and more engaging, but the structured method led to better performance and more meaningful reflection. There are a few key takeaways:

- Ease vs. effectiveness: The scratch test was easier to understand and quicker to perform, but fewer students identified materials correctly with it. The structured Vickers test, though slower and more technical, gave more accurate results.
- Performance difference: 6 out of 11 students correctly identified all materials using the Vickers test, compared to 3 out of 11 with the scratch test.
- Student preference split: While most enjoyed the simplicity of the scratch test, 7 out of 11 students still recommended the Vickers test to others for its clarity and structure.
- Knowledge gaps: Several students struggled with basic concepts like magnetism or material behaviour, suggesting that neither test alone is enough to fully support deeper understanding.

Overall, the results confirmed that intuitive methods offer an engaging starting point, but that structured testing is more effective for developing accurate material reasoning.

Figure 8. User Test 1 - Structured Part

Figure 9. User Test 1 - Intuitive Part

2.6 Conclusions

The exploratory analysis helped shape the technical and educational direction of the project. Different materials, properties and testing methods were explored, always with safety, simplicity, and classroom practicality in mind.

The small user test comparing a scratch test and a simplified hardness method revealed more than just a preference. While students liked the intuitive, feel-based approach, the structured test gave clearer results and helped them understand the property better. That difference wasn't expected to stand out so clearly, but it did.

It brought up a bigger question: What kind of learning should the setup actually support? Engagement and exploration are clearly valuable, but they don't guarantee understanding. Just giving students hands-on tools isn't enough if they can't interpret what they're doing.

To move forward, the project needed a closer look at the UPE curriculum. What are students expected to learn, and how is that currently taught and assessed? These questions shaped the next phase: a contextual analysis to make sure future design decisions are aligned with actual learning goals.

3. Contextual Analysis

Following the earlier exploratory analysis of materials, testing methods, educational practices, and initial user testing, it became clear that a deeper understanding of the curriculum structure was needed. This chapter builds on those findings by examining how constructive alignment and experiential learning principles related to material education within the UPE course.

This chapter identifies how the project could better support meaningful student learning by analysing learning objectives, teaching activities and assessment methods. Based on these insights, the project's design brief was refined, shifting the focus from material identification toward teaching material properties and scientific measurement skills.

Note: After the update to the design brief, the goal of the setup shifted from material identification toward understanding material behaviour. As a result, no fixed shortlist of materials or methods was defined at this stage. Instead, the tables in this appendix show a wide range of possible materials, properties, and testing methods that were explored in the early technical analysis. These lists served as references for feasibility, relevance, and educational value throughout the project.

3.1 Constructive alignment

Constructive alignment (Figure 9) is about making sure students aren't just learning theory for the sake of it but are actually doing the kinds of things they're expected to understand (Radboud University, n.d.). That means the learning goals, how things are taught, and how students are assessed all need to line up. In the UPE course, students are supposed to understand material properties and apply that knowledge to design decisions. But right now, most of that happens through lectures and theory. There's not much room to actually test or experience how materials behave.

Right now, there's a clear gap between what students are expected to understand and what they actually get to experience. The course asks them to apply material knowledge in design and engineering decisions, but most of that knowledge is taught through theory. Without the chance to physically test or observe how materials behave, it's hard for students to connect those concepts to real-world situations. This disconnect makes the learning feel abstract, and it limits their ability to build practical understanding.

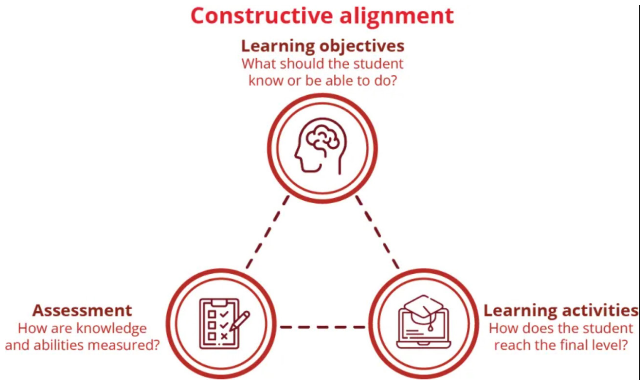


Figure 9. Constructive Alignment

3.2 Learning Objectives

The course works with learning objectives; specific, measurable statements that define what learnings should be able to know or do after completing the coures. There are two learning objectives in the UPE course that relate to material aspects:

- LO 1.2: Analyse existing products with respect to materials and production techniques.
- LO 1.4: Understand and apply basic material properties in product design.

These learning objectives' goal is to teach students to evaluate materials based on mechanical properties (e.g., strength, flexibility) as well as environmental factors such as sustainability.
Tools like Granta Edupack are used systematically to explore opportunities and limitations of different materials. Students practise this by analysing real product components during workshops, assessing materials for performance, production feasibility, and sustainability. This approach supports students in making informed material choices in future design challenges.

3.3 Learning Activities

Material education in the UPE course combines lectures, practical workshops, and self-directed study.

Lectures introduce key concepts, including material properties and manufacturing processes.

- **Workshops** allow students to analyse real-world product components, applying theoretical knowledge to practical examples.
- **Self-study assignments** and **tutorials** support skills in using tools like Granta Edupack, guiding students through case studies and analysis exercises.

This combination of lectures, workshops, and guided self-study is meant to help students develop the ability to select and evaluate materials independently in design contexts.

An important practical skill expected in the UPE course is the ability to accurately measure material dimensions using callipers. However, according to the course coordinator, student performance in this area has shown consistent challenges, affecting the reliability of material testing and analysis. To address this gap, the hands-on setup should include tasks where students measure dimensions directly using callipers or similar tools.

3.4 Assessment

Assessment of material determination knowledge in the UPE course takes place primarily through a final exam, an example question can be seen in Figure 10. The exam tests both theoretical understanding and practical application by presenting students with data from different testing methods:

- Visual inspection
- Fluid column testing
- Tensile strength measurements
- Weight and volume analysis.

Students are required to analyse these test results and determine the most likely material using Granta Edupack. The exam focuses not only on arriving at the correct answer but also on explaining reasoning and justifying choices, so students demonstrate scientific thinking rather than relying solely on intuition.

This assessment approach mirrors real-world engineering challenges, where incomplete data and the need for analytical reasoning are common.

Hiernaast is een vork afgebeeld waarvan we het materiaal willen determineren.
Naast visuele inspectie hebben we waar mogelijk de proef met de drie vloeistofkolommen uitgevoerd, de trekbankproef, het onderdeel gewogen en het volume bepaald met de maatcilinder ("graduated cylinder").
De gegevens van de drie vloeistofkolommen zijn:
. Water-ethanolmix: 0.90 [kg/l];
. Water: 1.00 [kg/l];
. Water-zoutmix: 1.25 [kg/l]

Visuele inspectie	We kunnen wel een code vinden maar deze is niet goed afgedrukt, het kan een 2 of 5 zijn.
Vloeistofkolommen	Dit materiaal drijft net onder de waterspiegel van de water-ethanolmix.
Trekbank	Dit materiaal gaat plastisch vervormen bij 25 [MPa] en breekt bij een trekspanning van ongeveer 40 [MPa].
Weegschaal en maatcilinder	De vork weegt 2.3 [gram]. Het product zinkt niet in water waardoor we het volume niet kunnen meten.

2p 7 Van welk materiaal is deze vork gemaakt? Gebruik Granta Edupack op level 2 met gemiddelde waarden en laat zien hoe je aan het antwoord komt. [2 punten]

Figure 10. Exam Question Example

3.5 Productive Failures

The workshop part of the course uses Productive Failure (PF) as a core teaching method (Figure 11). Students are first asked to tackle unfamiliar problems without much instruction. This often leads to incomplete or incorrect solutions, and that's exactly the point. The struggle helps them realise what they don't yet understand. After all, there are more ways to get something wrong than there are to get something right. When theory is introduced afterward, they're more likely to engage with it meaningfully.

During discussions with the course coordinator and Stefan Persaud, PF was described as a key part of how the course is set up. It follows a deliberate cycle: students try things, get stuck, and only then receive the tools or theory to make sense of what happened. This mirrors the development model outlined by Persaud and Flipsen (2023). Rather than starting with explanation, UPE encourages students to first explore, mess up, and then connect the dots, which gives the learning more impact.

3.6 Experiential Learning

Experiential learning is a teaching approach where students actively engage with materials and reflect on their experiences to develop deeper understanding. According to the Experiential Learning Institute (n.d.), experiential learning promotes meaningful connections between theory and practice through active participation, reflection, and continuous improvement.

The UPE course already incorporates elements of experiential learning, particularly through workshops that involve material sorting and analysis exercises. These activities encourage students to connect their observations with broader concepts like durability, performance, and sustainability.

However, opportunities for deeper material exploration, particularly regarding mechanical properties and scientific measurement, remain limited. The focus currently leans more toward qualitative assessment rather than structured, quantitative testing of material behaviour.

This project aimed to build on the experiential learning framework already in place by offering students direct, structured interaction with material properties. By doing so, it intended to further support the development of engineering reasoning skills alongside intuitive material engagement.

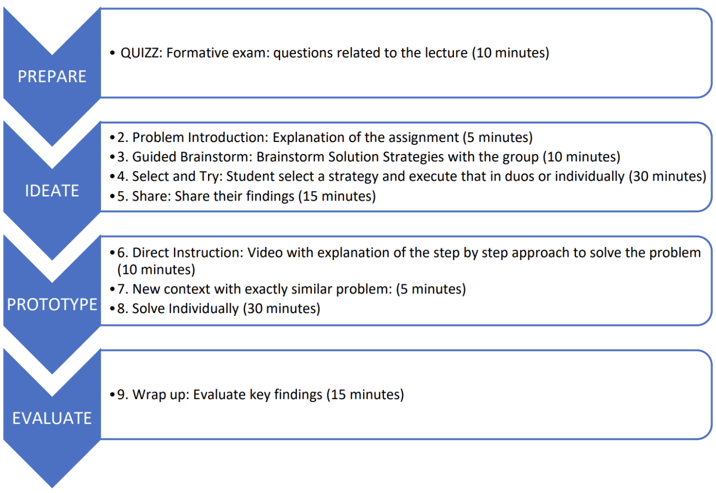


Figure 11. Productive Failures Workflow

Figure 12. Experiential Learning Workflow

3.7 Conclusions

The Contextual Analysis shows that while the UPE course already provides a foundation for experiential learning, there is significant potential to strengthen the connection between practical activities and intended learning outcomes.

Existing workshops offer valuable qualitative experiences, but hands-on activities targeting structured scientific understanding, such as measuring properties like hardness, stiffness, and density, are less developed. The exam structure clearly demands that students be able to reason analytically about material behaviour, not just recognise materials intuitively.

As a result, the original design brief, which focused on building a set of test setups for determining a shortlist of materials, required revision.
The new design focus became supporting the teaching of material properties and scientific measurement skills, helping students build both intuitive engagement and structured analytical capabilities.

This also reinforces the importance of Productive Failure within the course. By letting students first try, fail, and reflect before introducing formal theory, the setup doesn't just teach them what to think, it supports learning how to think. That principle helped shape the workshop structure and ultimately informed the requirements for both intuitive and structured testing.

Both previously identified concept directions offer strengths that align with this goal:

- Product pieces (PP) encourage intuitive understanding and contextual relevance.
- Standardised Material Pieces (SMP) provide clarity, structure, and reproducibility in scientific measurement.

Given the complementary nature of these two approaches, the final concept combines elements of both directions.

By integrating intuitive and structured experiences, the project supports both active engagement and the development of reliable engineering skills, aligning fully with the UPE course's educational objectives.

4. Key Findings & Main Drivers

Table X on the next page presents the key findings from the research, which have been translated into clear requirements. These findings highlight important needs, challenges, and opportunities identified during the study. Converting them into requirements helps guide the development process and ensures that the final solution addresses what really matters to users and stakeholders.

All requirements have been categorized under the Feasibility, Viability, and Desirability framework, which is commonly used in design thinking to evaluate whether a solution can be built (feasibility), is sustainable (viability), and meets user needs (desirability). A detailed assessment is provided in *Chapter 9.3*.

To steer the concept development and evaluation, a set of six Main Drivers was created by clustering the detailed requirements into core design goals. These drivers reflect the key insights identified earlier and cover both educational and practical priorities.

The challenge is to develop a setup that:

1. *Gets students physically involved with materials so they can build an intuitive sense of how materials behave through touch, observation, and simple interaction* (R1, R2, R13, R14, R26).
2. *Helps students understand and measure material properties in a clear and structured way, using repeatable tests and accurate tools* (R7, R12, R19, R26).
3. *Uses materials and test setups that feel realistic and relevant, similar to what students might see in actual products* (R8, R1).
4. *Gives results that are consistent and easy to understand, so students can draw clear conclusions and connect theory with practice* (R2, R12, R18, R19).
5. *Is practical to use in the classroom: quick to set up, easy to build, and made from standard, accessible parts* (R4, R5, R6, R23, R24).
6. *Can be used safely without supervision, with no sharp edges or destructive tests, and only low-tech components that are fully enclosed* (R3, R10, R15, R25).

Table 1. Key Findings into Requirements Table

Requirements Table
Key Insight
Students need to understand material behaviour, not just name materials
Combining structured and intuitive methods improves understanding
Setup must be safe for unsupervised student use
Setup must be portable across classrooms and workshops
Fast setup is essential to fit class time constraints
Hands-on setups must be low-cost to scale across large student groups
Setup must be usable in group settings without passive roles
Students need to practice structured measurement methods
Devices must be robust enough for repeated classroom use
Setup must be reproducible using standard tools and components
Students struggle with calliper use; setup must teach measurement
Students must be able to interpret results on their own
Setup must allow safe handling of all materials
Testing process should reinforce visual and tactile recognition
Devices must be storable and movable without damage
Setup must support independent exploration by students
Material selection must expose differences in physical behaviour
Device feedback must be clear without needing supervision
Setup must avoid high forces or risky components
Setup must include a range of testable properties
Scientific measurement skills should be embedded in testing
Practical constraints from course structure must guide design
The UPE course relies on Productive Failure in workshops. The setup must fit this teaching model.

#	Requirement	Category	Explanation
R1	The setup must support the teaching of material properties and scientific measurement.	Desirability	The updated design brief focuses on helping students understand material behaviour, not just identify materials.
R2	The setup should combine intuitive and structured testing methods.	Desirability	Combining intuitive and structured approaches improves student engagement and supports analytical skill development.
R3	The setup must be safe for independent student use.	Feasibility	Prior issues with unsupervised setups highlighted the need for a safe, certification-friendly design.
R4	The setup must be portable and easy to move between classrooms.	Feasibility	Flexibility across classrooms requires portable and easily movable setups.
R5	Setup time should not exceed 5 minutes.	Viability	Minimising setup time ensures workshop flow remains efficient and maximises learning time.
R6	The setup must be easy to construct using accessible tools and materials.	Feasibility	Simplified construction methods allow broader replication beyond TU Delft environments.
R7	The setup must allow for structured, reproducible measurement of at least one key material property.	Desirability	Supports the critical learning outcomes assessed in UPE's final exams.
R8	Materials used must be feasible to fabricate, affordable, and suitable for educational use.	Feasibility	Ensures that material selection for the setup aligns with cost, fabrication, and educational constraints.
R9	The setup must be durable and reusable across multiple student groups.	Feasibility	Durability ensures setups remain functional through repeated classroom use without significant maintenance.
R10	Students should be able to run the setup without supervision.	Feasibility	Safe independent operation reduces instructor workload and increases session flexibility.
R11	The setup should not overly rely on technology, but limited sensor or screen usage is acceptable.	Feasibility	Limited technology use prevents dependency while allowing appropriate feedback mechanisms like simple displays.
R12	Feedback from the test must be visible and understandable.	Desirability	Immediate, clear feedback reinforces learning during hands-on testing activities.
R13	The setup must support small group learning (max. 2 students) and active participation.	Desirability	Encourages active group work while avoiding large group dynamics that lead to passive participants.
R14	Each student must be able to interact physically with the setup.	Desirability	Physical interaction enhances experiential learning and engagement.
R15	The setup must not require expensive consumables for repeated use.	Viability	Keeps operational costs low and avoids consumables that would limit session scalability.
R16	The setup must be easy to maintain by staff and built to last across multiple course cycles.	Viability	Simplified maintenance allows course staff to repair or replace components easily between sessions.
R17	The setup should use intuitive use cues to guide students independently.	Feasibility	Use cues such as form, colour, or labels guide students intuitively through the testing process.
R18	The setup must visually link physical actions to observed results.	Desirability	Physically visible effects reinforce theoretical learning through practical observation.
R19	The setup must be affordable to produce at scale, targeting approximately €50 per unit for 75 setups.	Viability	Controlling per-unit cost enables feasible implementation across the full UPE cohort. Cost considerations influenced material selection, construction methods, and design simplicity.
R20	The setup must have minimal loose parts to avoid loss or confusion.	Feasibility	Reducing the number of loose parts simplifies setup, improves maintenance, and ensures clarity during workshops.
R21	The setup must use non-destructive testing methods to ensure materials are not damaged during testing.	Desirability	Using non-destructive testing methods enables repeated use of material samples and reduces classroom waste.
R22	The setup must allow students to practice and improve their ability to measure material dimensions accurately using callipers or similar tools.	Desirability	Integrating dimensional measurement tasks addresses known student difficulties with calliper use, reinforcing critical engineering measurement skills.
R23	The setup must be suitable for integration into the existing UPE curriculum and teaching model.	Viability	The UPE course uses Productive Failure as its core instructional approach in workshops. The setup must support this structure.

5. Concept Direction

Early in the project, two promising directions emerged from the exploratory phase. Both aimed to address the gap between theoretical knowledge and hands-on understanding of materials, but they did so in different ways. Each with its own focus, strengths, and limitations.

- Product Pieces (PP): This direction focused on using fragments from real-world products to spark intuitive engagement. It allowed students to interact directly with materials, scratching, tapping, comparing, and to begin forming mental models of properties like hardness, conductivity, or density. The emphasis was on reasoning and reflection through physical experience.
- Standardised Material Pieces (SMP): This track used clean, controlled samples to enable structured, measurable testing. These samples were better suited for exploring concepts like stiffness through repeatable methods and aligned more directly with engineering reasoning and learning objectives.

What initially appeared to be a question of sample format eventually revealed itself as a deeper educational split: one track supported intuitive, exploratory learning, while the other focused on structured reasoning and scientific analysis. Both approaches held value, but the curriculum analysis showed that the structured track responded most directly to unmet needs in the course, specifically, the lack of repeatable, data-driven testing that aligns with learning objectives and final assessment formats.

The Structured Track also presented more opportunity for meaningful design development. Building a setup that supports measurement, accuracy, and repeatability required a deeper design process, from initial concept generation through prototyping, mechanical refinement, and user testing. In addition, it offered a more complex design challenge, which made it a more fitting focus within the scope of this thesis.

The Intuitive Track, in contrast, builds on activities already present in the UPE course, such as informal material sorting and recognition tasks. Its purpose is to lower the entry barrier for students and spark engagement at an early stage, through hands-on, sensory interaction and reasoning. While it plays a valuable role in the combined setup, it required less redesign and fewer iterations and was thus condensed in this report.

For these reasons, the main chapters of this report focus on the Structured Track. It is the part of the setup that required the most extensive design work and most directly addresses the educational gaps identified in the analysis. The Intuitive Track remains part of the final combined setup and is described further in *Chapter 8 (Final Design).* Its full development process, including ideation, iterations, and user testing, is included in Appendix D.

6. Conceptualization

This chapter outlines the development of the structured material property testing setup. The goal was to design a hands-on tool that allows students to explore and measure a specific material property in a controlled, repeatable way. The process began by defining the educational goal, followed by an exploration of potential testing methods. These were narrowed down through evaluation against six core design drivers, leading to the selection and refinement of the final concept.

6.1 Goals

The structured sesting Track was set up to help students understand a specific material property through a measurable, repeatable test. Unlike the intuitive tools, this part needed to focus on accuracy and reproducibility.

Rather than developing several underdeveloped tools, the choice was made to focus on one clear, accurate, and educational setup. Based on earlier exploration of testing methods (*see Exploratory Analysis)*, stiffness was chosen as the focus, specifically measured through Young's modulus. Several alternative testing methods were considered based on prior research but were ultimately excluded due to concerns over safety, complexity, or limited relevance. A summary of these rejected methods can be found in Appendix E1.1.

Three-point bending was selected as the final method because it offers a safe, low-force, and material-efficient way to evaluate stiffness using simple components, making it ideal for classroom prototyping and exploration.

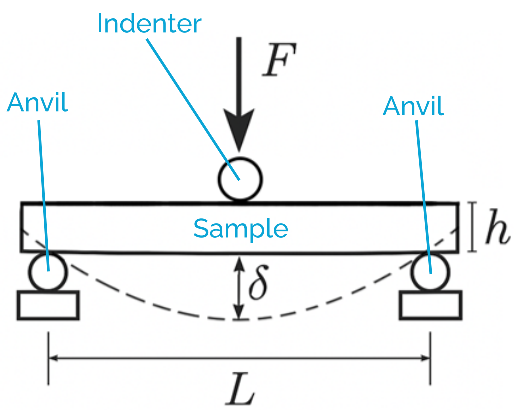


Figure 13. 3-point bending illustration

An illustration of a three-point bending test setup can be found in Figure 13. Its formula (ASTM, 2017; ISO, 2019) to calculate Young's modulus is as follows:

$$E = \frac{FL^3}{48I\delta}$$

E = **Young's modulus**, in MPa (megapascals)
F = **Applied force at midspan**, in N (newtons)
L = **Support span** (distance between supports), in mm
δ = **Midpoint deflection** (vertical displacement), in mm
I = **Second moment of area** (moment of inertia), in mm^4

Where:

$$I = \frac{wh^3}{12}$$

w = **Width of the sample** (horizontal dimension), in mm
h = **Height** (thickness) **of the sample** (vertical dimension), in mm

Young's modulus is a key property in engineering but often misunderstood. During earlier user testing, students frequently confused stiffness with strength, revealing a gap in understanding. It is defined as the slope of the linear portion of the stress–strain curve in the elastic region (Callister & Rethwisch, 2020). In bending tests, it can be described as the ratio of stress to strain in the initial, linear part of the force-deflection curve (Beer et al., 2012). Typically, this is measured in the very small deflection range of about 0.1 to 0.5 mm, where the material behaves elastically.

Measuring Young's modulus precisely in this initial elastic range is challenging within the scope of this project due to constraints such as low cost, quick build time, and simplicity. Therefore, the project settles for an effective modulus, calculated from a slightly larger, more stable portion of the deflection curve. While this is not the exact Young's modulus, it provides consistent, repeatable results suitable for classroom use. A more detailed explanation of the effective modulus is provided in Appendix X.1.

6.2 Ideation

The Young's modulus formula clearly shows that both the applied force (F) and the deflection (δ) are critical variables in calculating material stiffness. This means that accurate measurement of these quantities is essential to obtain meaningful results.

To address this, the system was divided into key subsystems: the force input (responsible for applying F), force transmission (which ensures F is properly conveyed through the setup), force measurement (which quantifies the actual force applied), and deflection measurement (which records δ, the material's deflection). These components formed the basis of a morphological chart (Figure 14) during ideation.

6.3 Concepts

After mapping out different subsystem options in the morphological chart (Figure 14), three full concept directions were developed. Each one builds on the basic 3-point bending setup but takes a different approach to how force is applied, how deflection is measured, and how feedback is given to the student. The aim wasn't to find the most high-tech solution, the focus was on exploring different trade-offs between simplicity, clarity, and precision, while keeping things realistic to build.

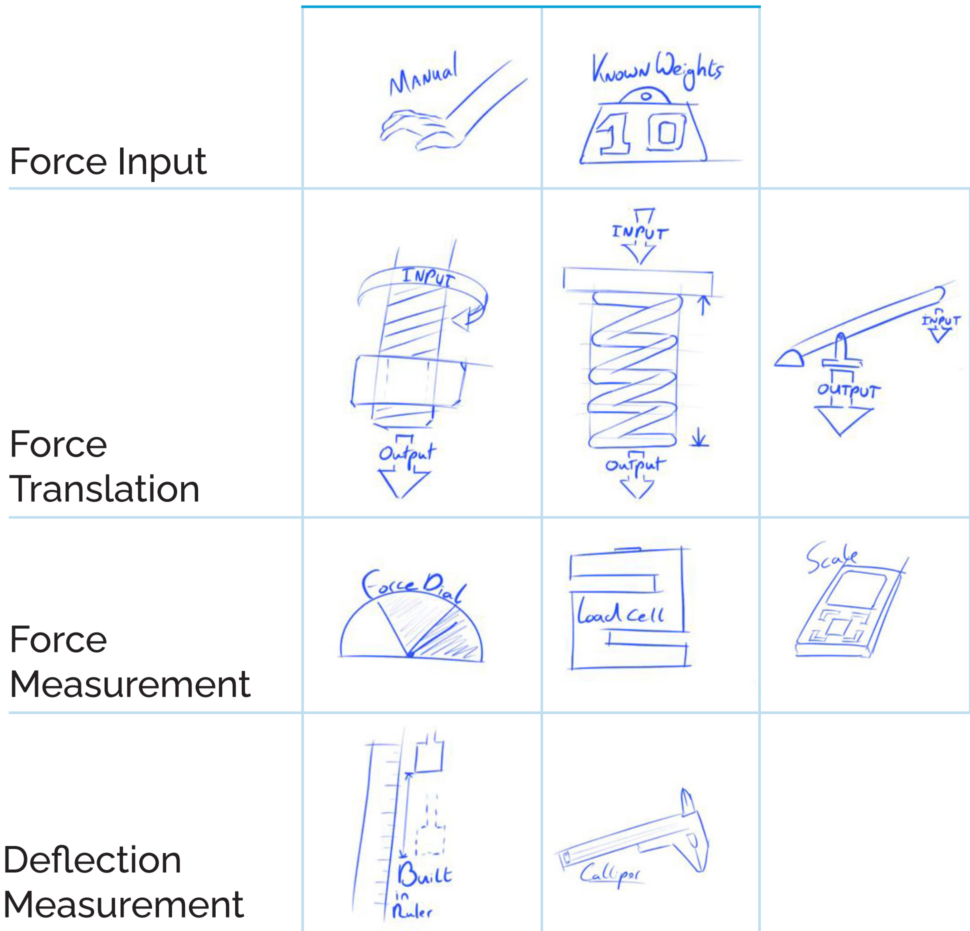


Figure 14. Morphological Chart

Concept 1: Screw-Driven Indenter with Load Cell

This concept uses a hand-turned M8 screw to apply force. The screw moves a nut inside an indenter which can only move up or down, which then presses down on the sample. A scale underneath one of the supports measures the applied force. Deflection can be observed using a ruler or visual marker next to the sample.

- The screw gives consistent, controlled input.
- The load cell allows for accurate measurement.
- 3D printed parts keep the design compact and replicable.

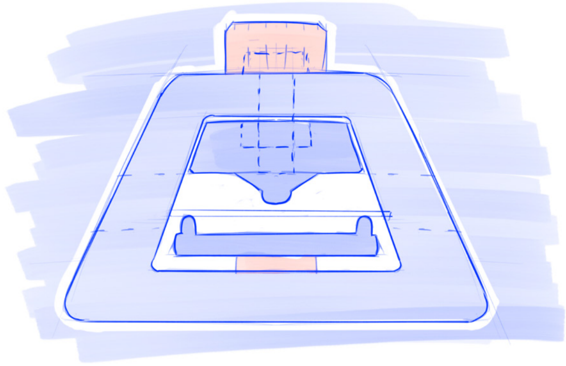


Figure 15. Concept 1

Concept 2: Spring Plunger with Visual Indicator

In this setup, the student presses down on a plunger that compresses a spring. A printed colour band or scale shows how far the spring is compressed, which can be used to calculate the force put on the indenter. While it doesn't give precise force values, it offers a way to compare applied force visually. The sample rests on fixed supports, and deflection is shown using a small scale or marker.

- It resets automatically and doesn't require electronics.
- The spring provides resistance and some repeatability.
- Less accurate, but easy and quick to use.

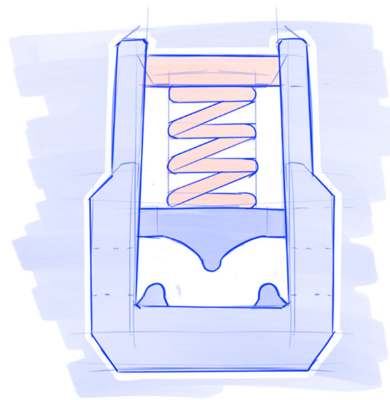


Figure 16. Concept 2

Concept 3: Weighted Lever with Deflection Stops

This concept has a small lever arm that applies force onto the sample. Students place weights at different points along the arm to vary the load. Deflection is measured by a ruler.

- Known weights give a consistent input force.
- Setup is fully mechanical and visual.
- Takes more space and slightly more setup time.

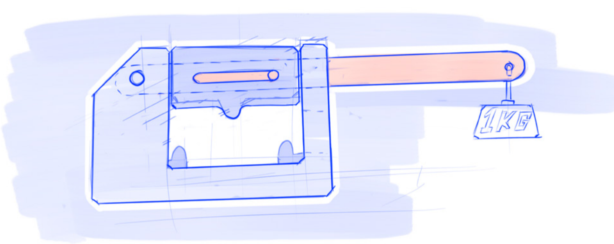


Figure 17. Concept 3

6.4 Evaluation

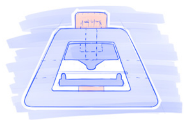
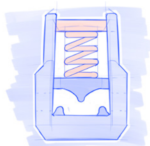
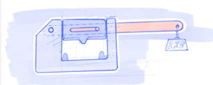
The three developed concepts were evaluated using the six Main Drivers defined earlier in the project. A simplified overview of the evaluation is shown in table 2. The full matrix with justifications is included in Appendix E3.

Concept 1 was chosen for further development. It gave the clearest, most measurable results, while still being compact and easy to replicate. While the load cell and wiring added some complexity during assembly, it was the only option that offered real force values, which made it much better suited for teaching students how force, deflection, and stiffness are connected.

Concept 2 was more intuitive and easier to use, but the lack of precise feedback made it less useful for understanding the theory behind the test. It also relied heavily on the consistency of the spring, which could vary between setups.

Concept 3 stood out for its visual clarity, but had issues with repeatability, safety, and space requirements. Moving weights around introduced some risk, and while the lever principle could easily generate sufficient force with a long enough arm, the setup wasn't as compact or straightforward to use in a busy classroom setting.

Table 2. Evaluation Matrix

Concept			
1. Engagement			
2. Scientific Precision			
3. Real-world Relevance			
4. Reproducibility			
5. Practicality			
6. Safety			
Outcome			

7. First Iteration

This chapter documents the first complete design iteration of the structured testing setup. The main objective was to develop a version that is mechanically reliable and educationally effective, with an initial focus on measuring material stiffness at relatively low force levels. Prototyping was employed as an iterative learning process, allowing each version to reveal new challenges, requirements, and opportunities for improvement. The aim was to validate core mechanisms and usability before scaling the system to accommodate higher forces and a wider range of materials in later iterations.

The chapter is split into two parts. Section 7.1 describes how the setup evolved across several prototypes, focusing on changes to the force input, measurement stability, and user interaction. Section 7.2 covers the first round of testing. This includes both user testing, to assess whether the setup helped students understand material stiffness, and mechanical evaluation, to check consistency and identify weak points. The insights gained from both parts fed directly into the final design described in *Chapter 8* and contributed to the validation in *Chapter 10.*

7.1 Prototype Evolution

All detailed information and documentation related to the development of the prototypes described in this chapter can be found in *Appendix E4.*

Prototype 1 – Proof of Principle

This initial prototype tested whether an M8 bolt could apply enough controlled force to visibly bend an aluminium strip. It was 3D-printed in two parts with a captive nut to keep the bolt aligned while rotating. M8 was chosen for its balance of speed and control, and compatibility with standard hardware. The aluminium strip bent as expected, confirming the concept (Figure 18).

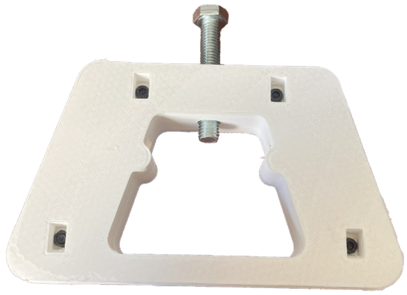


Figure 18. Prototype 1 - Proof of Principle

Prototype 2a – First Integrated Version

The bolt was fixed in a 3D-printed housing, driving a printed indenter that moved vertically while being prevented from rotating. A 3D-printed support with two flat anvils held the sample for three-point bending. Cantilever tabs on the indenter and support allowed calliper-based deflection measurement without interfering with the sample. Force was initially measured using a precise kitchen scale (max 200 g), and the bolt was turned with a wrench (Figure 19).

Figure 19. Prototype 2a - First Integrated Version

Prototype 2b – Functional Refinement

A 3D-printed knob replaced the wrench for smoother, more intuitive operation. Backlash was reduced by redesigning the indenter with two nuts preloaded to eliminate play. The deflection setup was improved by adding a slot in the housing for a calliper, allowing direct and repeatable measurement of the indenter's deflection tab (Figure 20).

Figure 20. Prototype 2b - Functional Refinement

Prototype 2c – Finishing Touches

The kitchen scale was replaced by a 5 kg button load cell bolted to the support for more consistent force readings. To avoid errors from anvil flex, deflection was measured between the indenter tab and support, isolating the sample's deformation. The indenter and support were modified with contact points for the calliper to improve accuracy without added complexity. An 8-digit display was added to show load readings, though electronics were still external (Figures 21 and 22).

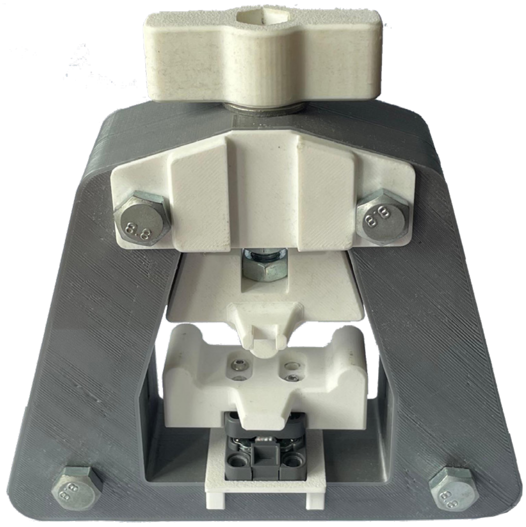


Figure 21. Prototype 2c - Finishing Touches

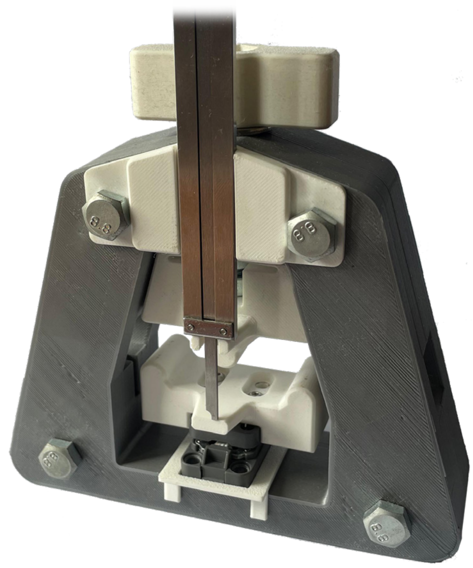


Figure 22. Prototype 2c in use

7.2 Evaluation

7.2.1 User Testing

To explore whether combining theory and hands-on testing helped clarify abstract concepts like stiffness, and whether the setup supported that process effectively, a user study was conducted. Eight first-year IDE students completed both a theoretical Young's Modulus calculation and a physical 3-point bending test using the prototype. Before, during, and after the session, they answered reflection questions about their understanding, confidence, and learning preferences. The full user test study can be found in Appendix G.

Conclusions

The structured testing setup helped students move from abstract understanding to practical insight. Most began with vague or partial ideas about Young's Modulus, typically linking it to stiffness or bending. After calculating the modulus and then performing the physical test, their understanding became more grounded and specific. The main takeaways of the user test can be found on the right.

Figure 23. First Iteration User Testing

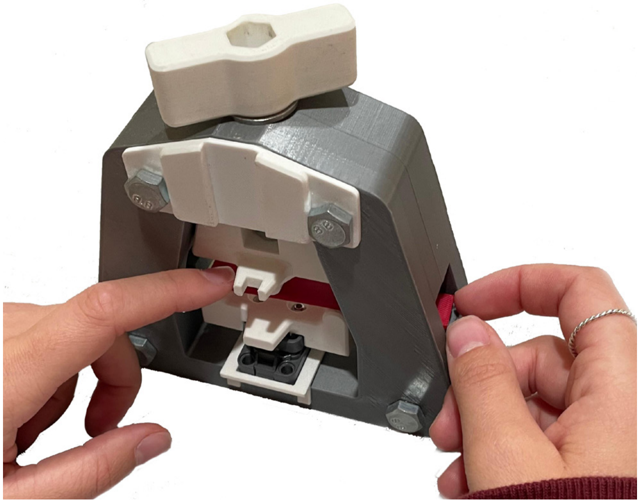


Figure 24. First Iteration User Testing

- Increased confidence and understanding: All students reported a clearer understanding after completing the hands-on test. Confidence scores generally rose from 2–3 (before) to 4–5 (after).
- Misconceptions addressed: Several students confused stiffness with hardness or assumed linear material behaviour. The test helped clarify these ideas through direct observation.
- Preference for physical-first learning: All students said they would teach the topic starting with the physical test. It helped them "see what the theory is actually about" and gave context for the formulas.
- Measurement challenges: Difficulties with unit conversions, material placement, and deciding when to take readings reinforced the importance of repeatability and precision in real-world testing.
- Setup feedback: Despite finding the experience valuable, students noted some issues:
  - *- The beam was hard to position consistently.*
  - *- The force reading fluctuated after turning, making it unclear when to measure.*
  - *- Instructions could be clearer, several asked for a checklist or visual guide. Setup moves around easily on the table.*
  - *- Rotating the knob feels rough, no feedback on when you hit material.*
  - *- Rotating knob can interfere with callipers when measuring.*

Even with these points of friction, students described the test as valuable and engaging. It helped bridge the gap between calculation and comprehension, fulfilling the educational aim of the structured track.

7.2.2 Mechanical Evaluation

This mechanical evaluation focused on identifying early issues that could affect measurement reliability or ease of use. Tests (*Appendix E6*) were performed in a short timeframe and often informally, which means the results should be seen as indicative, not conclusive. However, several clear mechanical limitations emerged that helped steer the next design iteration.

- Deflection readings lacked consistency. The callipers pressed directly onto the indenter (Figure 26), which transferred force through the load cell. Because the button cell can tilt slightly, this introduced vertical play, causing deflection values to shift by up to 1 mm under higher loads (*Appendix E6.1*).
- Force adjustments were imprecise. The M8 screw mechanism had high rotational friction, making it hard to apply small, steady changes. This was worsened by the tensioned nut in the indenter, which removed backlash but added too much resistance.
- The load cell showed drift and sensitivity to placement. A small test showed a 4-5% deviation when the load was applied 10mm off-centre (*Appendix E6.2*). While not critical, it adds noise to the results and depends heavily on the sensor's internal stability.
- Beam alignment was unreliable. Students had difficulty placing the strip consistently, which affected load symmetry and output values. This confirmed the need for mechanical guidance or clear visual alignment cues (Figure 25.)

In short: the prototype worked, but not reliably enough. The mechanical issues identified here led to changes in the next iteration, including improved alignment, reduced friction, and a new sensor approach.

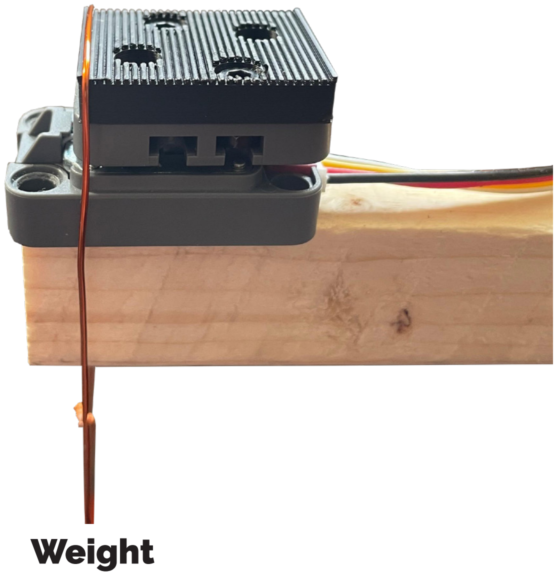


Figure 25. First Iteration Mechanical Evaluation - Off-axis load cell test

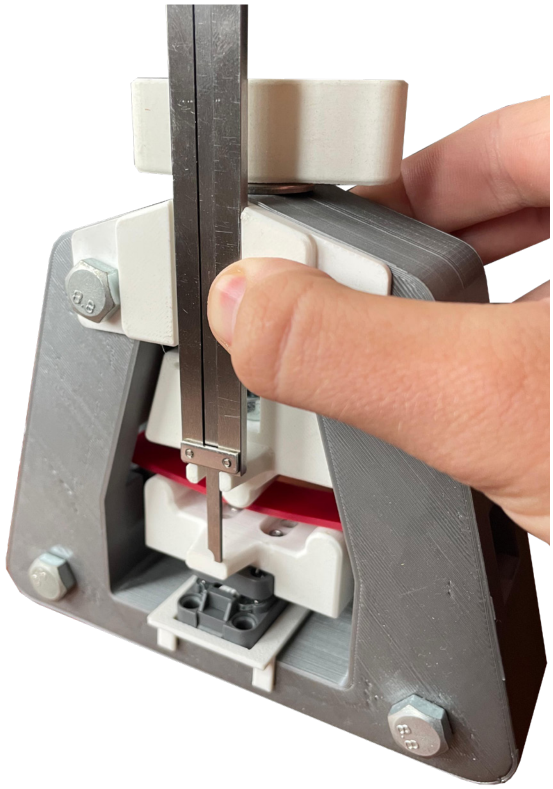


Figure 26. First Iteration Mechanical Evaluation -

7.3 Conclusion

This first design iteration showed that the setup works in principle. Students were able to measure material stiffness, connect it to theory, and build a clearer understanding of Young's modulus. The core mechanisms functioned, and the overall approach proved valuable in practice.

At the same time, several issues came to light. The high friction in the screw mechanism made it hard to apply force gradually. The load cell was sensitive to placement, sometimes drifted and tilted when the calliper was applied, influencing deflection readings. Students also struggled to position the beam consistently and had trouble deciding when to take measurements.

Despite this, the setup delivered useful results. The test helped correct misconceptions and made stiffness feel less abstract. Feedback confirmed the concept, but also made it clear where improvements were needed.

The next version should focus on:

- *Smoother force input*
- *Better sample alignment*
- *More stable deflection readings*
- *A more reliable sensor setup*
- *Small changes to improve ease of use.*

8. Final Design

8.1 Final Design (Structured Track)

The final setup is a compact, self-contained version of a classic three-point bending test (Figure 27). It was designed to give students hands-on insight into elastic deformation and material stiffness, without requiring lab infrastructure or supervision.

The device measures 108×116×40 mm, with a few minor protrusions along the width. The construction includes a fixed span of 40 mm, supported by two anvils, and a central indenter connected to a hand-turned knob. As the knob is rotated, the indenter presses downward onto the sample, see Figure 35 for the internal mechanism. A standardized sample size of 60x15x1,5mm was introduced.

Deflection is measured manually using callipers, which presses directly against the moving indenter (Figure 30). A vernier scale on the dial provides a coarse visual indication to help students understand how far the system has been turned (Figure 31), but the actual measurement is done via the calliper.

Force is measured using a straight bar load cell (TAL220, 10 kg) mounted under one of the supports. The load cell is connected to a microcontroller (Seeeduino Xiao), which calculates the weight and displays it on a small OLED screen embedded in the housing (Figure 32).

The frame is made from 5 mm laser-cut poplar wood, with 3D-printed parts in PLA for the indenter mechanism (Figure 34), supports, and internal structure. Instructional engravings are included on both sides of the device:

- The right-hand side (Figure 28) shows the formula for calculating Young's Modulus in a three-point bend test, along with parameter explanation.
- The left-hand side (Figure 29) includes clear usage instructions to support independent operation.

The setup allows students to explore the concept of stiffness through direct interaction, scientific measurement and calculation, while keeping the setup safe, portable, and easy to reproduce in other educational contexts.

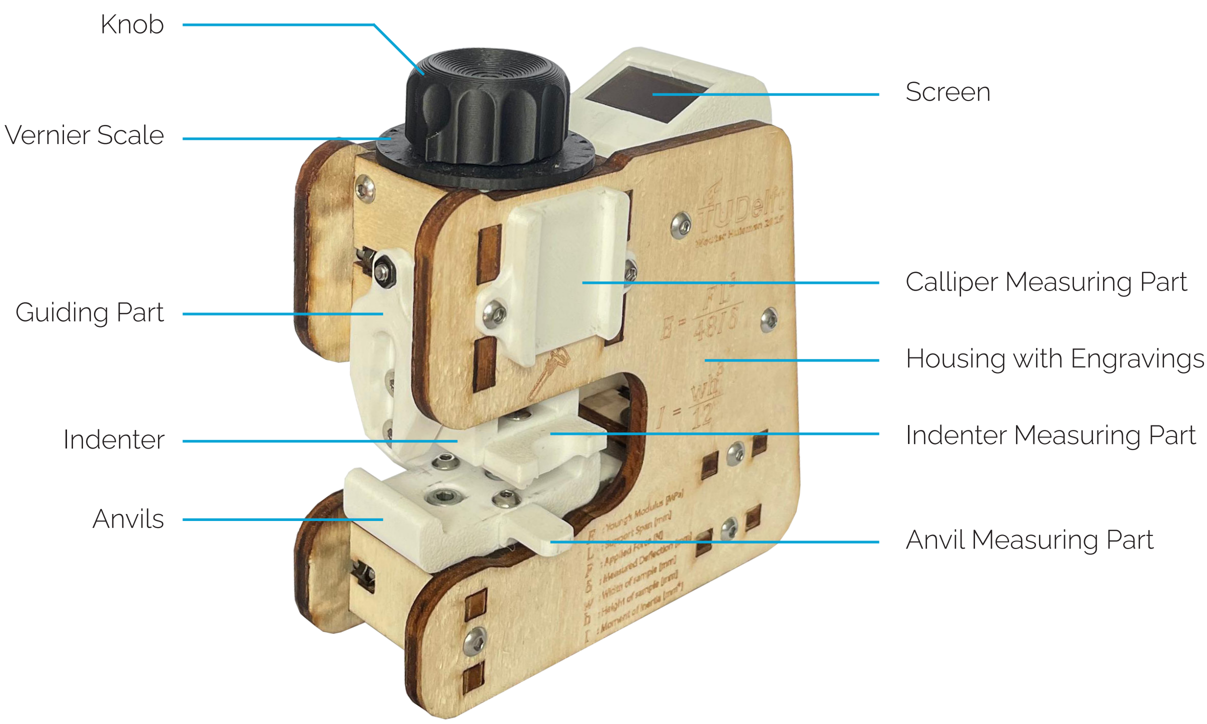


Figure 27. Final Design - Overview Image

Figure 28. Final Design - Left Side

Figure 29. Final Design - Right Side

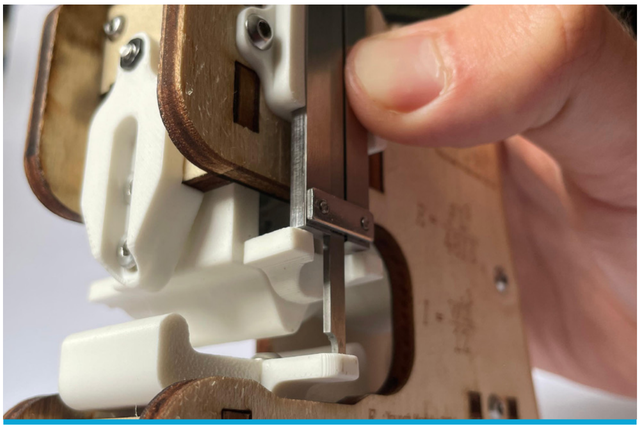


Figure 30. Final Design - Calliper Measurement

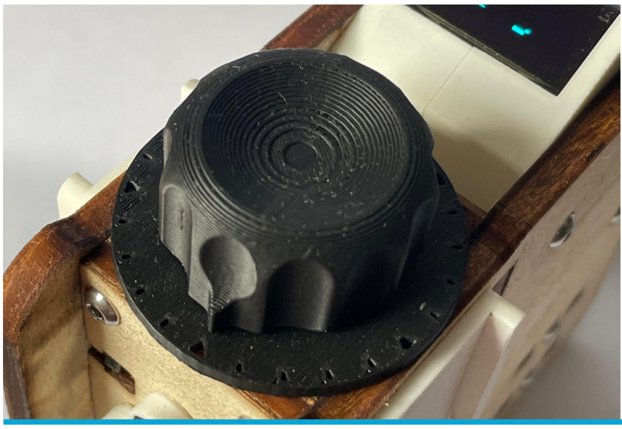


Figure 31. Final Design - Knob with Vernier Scale

Figure 32. Final Design - OLED Screen

Figure 33. Final Design - Indenter Guidance Mechanism

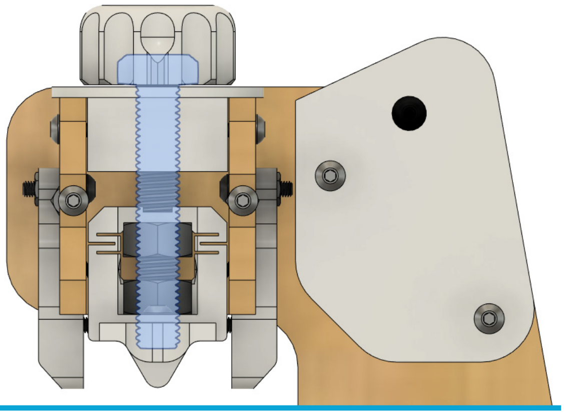


Figure 34. Final Design - Indenter Internal Mechanism

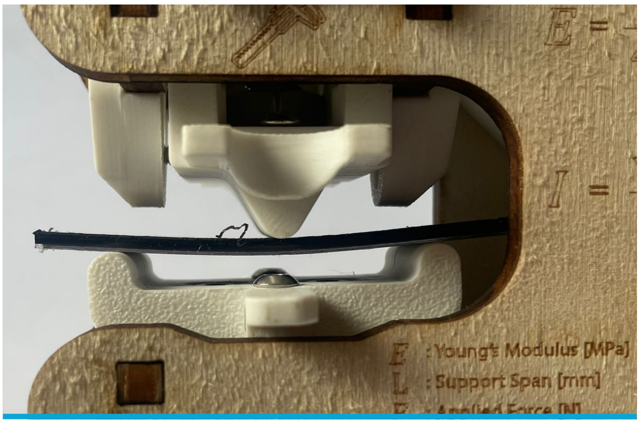


Figure 35. Final Design - in action

8.2 Iteration Summary

Following the mechanical evaluation (*Chapter 7.2.2*), the setup was fully redesigned to improve accuracy, build quality, and mechanical stability. Rather than refining the initial prototype, a new version was built from the ground up, incorporating a new housing approach, a new load cell and better mechanical guiding. The updates in Table 3 summarize the key changes made during this phase. Full technical documentation, sketches and justifications for updates can be found in Appendix E7–E8.

Table 3 Iteration Summary

Update	Purpose
Laser-cut housing	Replaced the 3D-printed frame with 5 mm poplar panels to improve rigidity, alignment and production speed.
Bar-type load cell	Upgraded from a 5 kg button cell to a 10 kg straight bar (TAL220) for more stable and higher force readings.
Dual-bearing bolt mount	Added two 608zz bearings to reduce friction and improve control when applying load.
Set screw alignment	Introduced four countersunk set screws to eliminate play in the indenter's vertical movement.
Vernier dial	Redesigned the main knob with a 25-division vernier scale to give students a sense of indenter movement during use.
Electronics	Embedded a Seeeduino Xiao and HX711 amplifier in a sealed compartment with OLED display for live force output.
Geometry updates	Adapted the span and indenter shape using ISO 178 and ASTM D790 guidelines to improve reliability across materials.

8.3 Intuitive track Reintroduction

As introduced in *Chapter 5*, the Intuitive Track was developed alongside the main setup but deliberately left out of the core design chapters. This is where it returns. Not as an add-on, but as a foundational part of the full learning experience.

The tools in this track (Figure 36) form the basis of a short preparatory workshop. Their aim is simple: get students to physically interact with materials before diving into measurement and theory. Each tool targets a specific property (e.g. hardness, magnetism, conductivity) and invites students to explore through touch, observation, comparison and reasoning. *Chapter 9.1.1* shows figures of all tests in use.

This stage isn't about accuracy. It's about awareness. The tools help students confront assumptions, notice differences, and start forming ideas they can later test. The Intuitive Track acts as a warm-up, not in importance, but in level of complexity. The final set includes five tools:

- Scratch Test – Surface hardness, felt directly
- Magnetism Test – A basic probe to check for magnetic behaviour
- Conductivity Test – USB-powered LED circuit that lights up on contact
- Thermal Conductivity Test – USB-powered element to compare thermal transfer
- Density Test – A submersion setup that links weight to volume

Each tool is low-tech, robust, and safe to use without supervision. Together, they create a tactile entry point into material behaviour which supports engagement before precision. A container was also made to store the smaller parts. The full development process, including user feedback and design rationale, is documented in Appendix D.

Figure 36. Intuitive Tests - Overview

8.4 Combined Setup Overview

The final setup combines two parts: a set of intuitive tools and a structured testing device (Figure 37). Each has a different role in the learning process, but they are used together as part of a two-part workshop format. Most likely, each setup will be used in its own session.

The intuitive tools are used first. These are low-tech, hands-on tests that let students explore material properties through observation and direct interaction. The goal is to get students thinking about differences between materials without needing prior knowledge. It's mainly about recognition, comparison, and triggering questions. After that, the structured setup is introduced.

This part focuses on one property, stiffness, and asks students to measure, calculate, and interpret. It connects to theoretical knowledge but also highlights things that theory often skips. How hard it is to get accurate data, what measurement error looks like, and how real material behaviour can be messy.

By using both tracks in sequence, students move from open exploration to structured reasoning. The aim is to support both curiosity and technical understanding, especially the shift from "what is this material?" to "how does this material actually behave, and how do I measure that?".

Figure 37. Combined Setup

8.5 Bill of Materials

A full Bill of Materials (BOM) is included in Appendix G2. It covers all parts needed to build one complete setup, including both the intuitive and structured track tools. Most components are standard (things like 3D-printed parts, off-the-shelf electronics, and basic hardware) chosen to be cheap and easy to source.

The total material cost for a single, one-off build comes out to €87.91. When scaled to 75 units (as required for full course rollout), the price drops to €39.43 per unit. That big price difference is mostly due to parts used in the intuitive tools , especially small electronic components that can only be ordered in bulk. The structured device is cheaper and scales better: €31.86 for one, €19.70 in bulk.

Labour and production costs aren't included. For now, it's assumed the setups are made using university machines. Assembly time is estimated at 1 to 1.5 hours per device. Labour isn't included in the cost, but it would make a noticeable difference. That said, if setups are assembled in batches, like a mini production line, the time and cost per unit would drop significantly.

A stacked bar graph in Figure 38 shows how much each part of the setup contributes to the total cost, both for a single unit and in bulk. It gives a clear picture of where the money goes and why bulk pricing makes such a difference.

Table 4. BoM Table

Device	One off Cost	Bulk Cost (75pc)
3 point bend Test	€ 31,86	€ 19,70
LED Test	€ 10,93	€ 3,00
Heat Test	€ 8,59	€ 5,17
Density Test	€ 25,84	€ 10,09
Magnet Test	€ 5,29	€ 0,08
Scratch Test	€ 3,51	€ 0,04
Storage Box	€ 1,90	€ 1,36

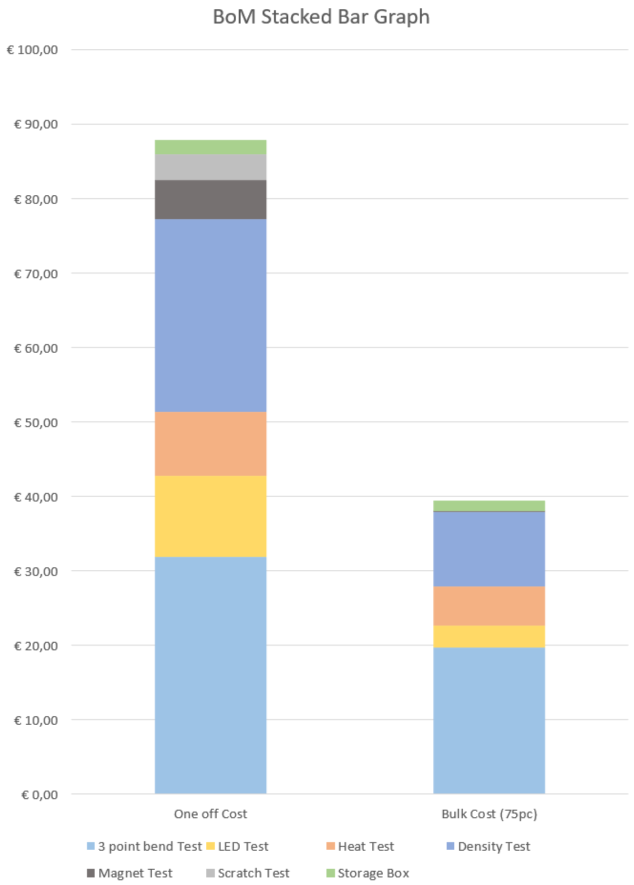


Figure 38. BoM Stacked Bar Graph

8.6 Manufacturing and Assembly

This section outlines how the final setup is constructed, which manufacturing methods were used, and how the assemblies fit together (Figure 39). The design was made with future replication and educational reuse in mind and an Instructables page is currently in development. In the meantime, the documentation and figures in this section provide a clear overview of the internal structure and assembly.

8.6..1 Manufacturing Methods

The setup consists of a mix of laser-cut and 3D-printed parts.

- All white parts in the figures are 3D-printed from PLA using FDM printing.
- All wood-coloured parts were laser-cut from 5 mm poplar plywood.

The outer housing is constructed from laser-cut side panels and three connection plates. These plates house press-fit M3 nuts, which allow the outer plates to be slotted on and fastened using M3 bolts. This system keeps the housing rigid, modular, and easy to disassemble.

Mechanical components such as the indenter, guides, and mounting elements were 3D-printed in-house. Electronics, screws, bearings and other standard components were sourced externally. An overview of all parts can be found in Appendix G2.

8.6.2 Assembly Overview

The setup is made up of two functional assemblies sandwiched between the housing plates: the Indenter Assembly and the Electronics Assembly.

Indenter Assembly
At the core of the indenter assembly (Figure 40) is an M8 bolt, which runs vertically through the system. A knob is mounted on top, and directly beneath it is a vernier scale for indicative movement. The bolt passes through two ball bearings, which are clamped into the housing for alignment and stability.

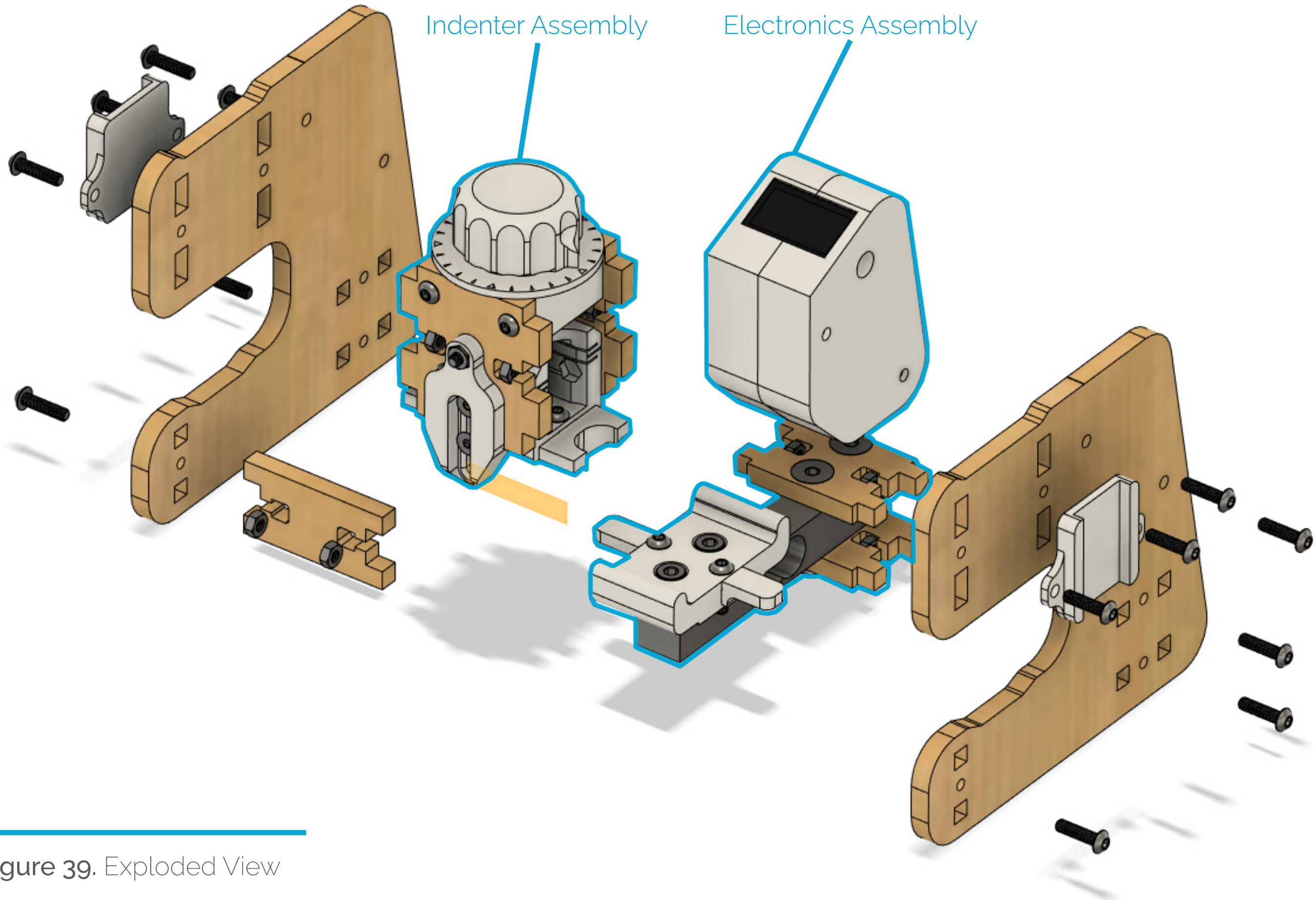


Figure 39. Exploded View

Lower down, the bolt passes through a 3D-printed indenter part. This part contains two M8 nuts, which are placed under slight tension by the geometry of the indenter itself, they are held apart just enough to stay preloaded and locked in place.

On either side of the indenter are 3D-printed guiding rails. These are slotted into the plates that also mount the bearing housing. The heads of four m3 countersunk set screws, that are screwed into the indenter part, slide through the housing. This construction ensures the indenter can only move vertically, with minimal play on other axes.

Electronics Assembly
The electronics are mounted in two electronic housing parts (Figure 41). This assembly also includes a pair of anvil components that interact with the load cell and test samples.

The internal electronics are:
- A Seeed Studio Xiao, snap-fitted into a printed bracket.
- An HX711 amplifier, screwed onto two printed standoffs.
- An OLED display, which is clamped between two housing plates, with no fasteners required.

7.3 Replication and Reuse

The setup was designed to be reproducible using commonly (makerspace) available tools like a laser cutter and 3D printer. All parts were intentionally kept low-cost and widely available. While a detailed step-by-step build guide is still in progress (instructables). Once finalized, the Instructables page will provide further guidance, including additional photos and build steps.

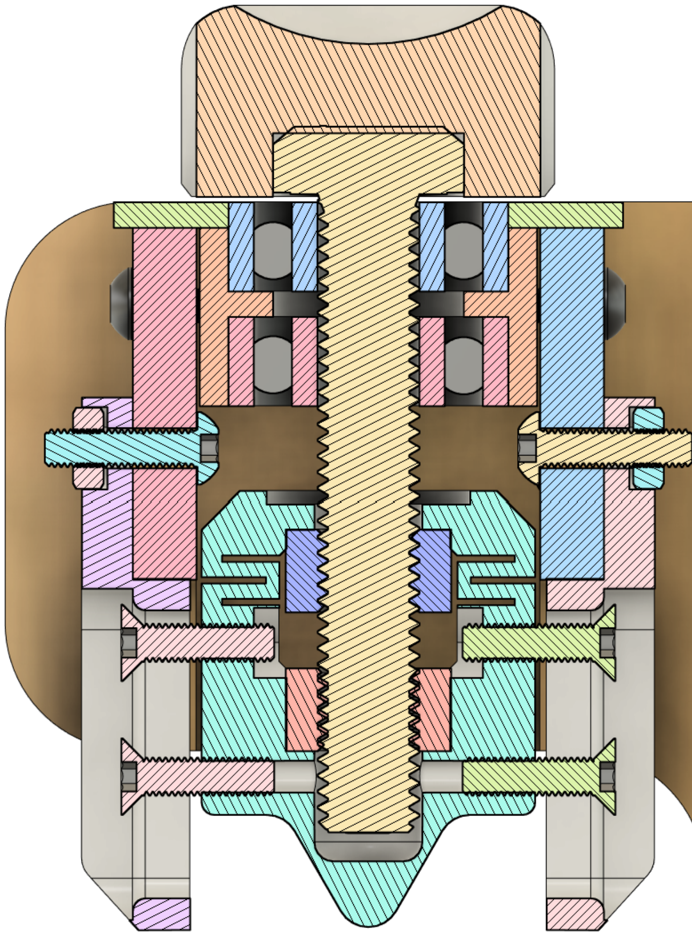


Figure 40. Indenter Assembly Section View

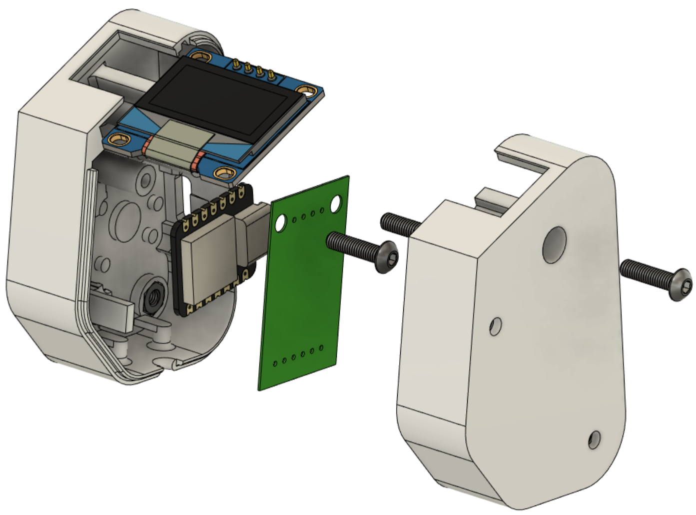


Figure 41. Electronics Assembly Exploded View

9. Validation

This chapter looks at whether the final setup meets the project's requirements. Validation is split into three parts. First, a workshop was run with IDE students to see if the device supports the kind of reasoning and learning the UPE course aims for. Second, the setup was tested mechanically to check if it delivers consistent and useful measurements. These two parts form the basis for the third and final section: an evaluation of how well the design scores on feasibility, viability, and desirability.

9.1 Educational Validation

To validate whether the setup meets the project requirements related to the educational goals of the UPE course, two workshops were developed together with feedback from the course coordinator and tested with students. These workshops were not intended to showcase the tools, but to assess whether they effectively support the kind of reasoning and engagement the course aims for. This includes requirements concerning intuitive exploration, structured understanding, and independent learning. The workshop structure follows the Productive Failure model used in UPE. The goal was to test whether the setup supports that learning cycle in practice.

Each workshop targets a different aspect of material reasoning. Workshop 1 focuses on material identification using only sensory input and simple physical property tests (e.g. magnetism, hardness, density), to assess whether students can shift from intuition to informed classification. Workshop 2 asks students to estimate how much load a wooden bench can support, using a scaled model and a bending test device , challenging them to observe, measure, and discover patterns before being introduced to stiffness theory. Together, the workshops validate both the intuitive and structured aspects of the setup. The full workshops can be found in Appendix H2.

9.1.1 Validation

To evaluate the effectiveness of the workshops, a short user test was conducted with three student groups (five first year IDE students in total: one working solo, two pairs). All participants completed both workshops in full. Observations focused on reasoning development, behaviour, and interaction with the physical tools. An overview of all tests in use can be seen in Figures 42 through 47 and further details are documented in a full user study in Appendix H.

In Workshop 1, students first sorted unknown materials based on intuition, then refined their reasoning using five physical property tests: magnetism, scratch resistance, conductivity, thermal feel, and density. The density test stood out as a consistent turning point in how students justified their classifications.

In Workshop 2, students estimated how many people a bench could support, using a scale model and 3-point bending test setup before being introduced to the theoretical formula. Most participants used the model not just to collect data, but to explore patterns, challenge assumptions, and recognise the relationship between force, deflection, and geometry.

While prior knowledge influenced some behaviour, the workshops still produced clear realisation moments, where students shifted from guesswork to structured reasoning. The physical setups functioned as intended: they didn't just demonstrate a principle but actively supported conceptual understanding. Overall, the tools and structure proved effective in prompting the kind of reasoning the workshops aimed to support.

Figure 42. Workshop 1: Density Test

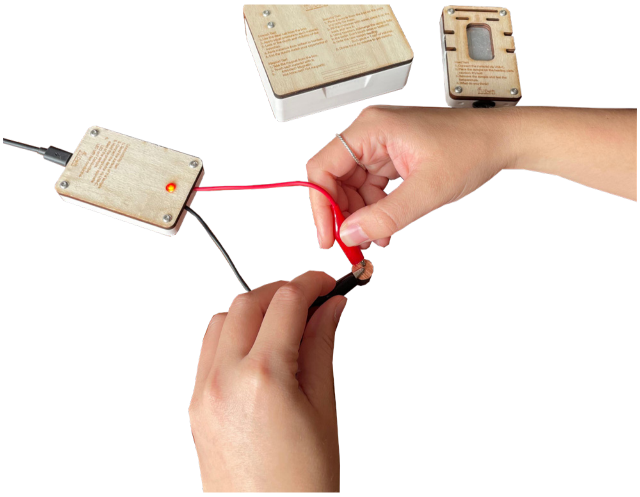


Figure 43. Workshop 1: Electrical Conductivity Test

Figure 44. Workshop 1: Thermal Conductivity Test

Figure 45. Workshop 1: Magnet Test

Figure 46. Workshops Timeline

Figure 47. Workshop 2: 3-Point Bend Test

9.2 Mechanical Validation

Having validated the setup's educational effectiveness, this part of the validation focuses on whether the final setup can provide reliable, interpretable data to support structured material testing in a classroom context. The goal here isn't lab-grade precision, but dependable and repeatable performance that helps students understand stiffness through hands-on experimentation. Supporting data, calculations, and setup details can be found in Appendix I.

9.2.1 What Is Being Measured

Like discussed before in *Chapter 6*, the device calculates an effective modulus, based on the slope between 1 mm and 2 mm of deflection. This skips the early, unstable part of the force–deflection curve, a region that's especially unreliable in materials like polymers due to surface effects and viscoelastic behaviour (Roylance, 2003). The result isn't a true material constant, but it's stable and repeatable enough to support comparison and structured reasoning, which is the actual goal in an educational setting. More background is included in Appendix I1.

9.2.2 Deflection Measurement

Deflection was measured manually using standard analogue callipers. Tests showed that small variations in placement or technique caused some fluctuation, but on average the repeatability error was around ±0.03 mm. Factoring in the resolution of the tool itself, the total uncertainty per reading comes out to roughly ±0.06 mm.

Since the effective modulus is based on the difference between two deflection points, this uncertainty directly affects the final calculation. Still, under typical classroom use, this level of accuracy is acceptable. The full setup and data are included in Appendix I2.

9.2.3 Force Measurement

To measure force, a 10 kg straight bar load cell (TAL220) was placed under one support and connected to an HX711 amplifier. The readings were checked using calibrated weights. Results were accurate across most of the range, with a typical uncertainty of about ±0.05 kg, or roughly ±0.49 N. The readings also showed occasional single-frame spikes in output, a known issue with the HX711 when unshielded. These were easy to spot and filtered out during data collection. More on this can be found in Appendix I3.

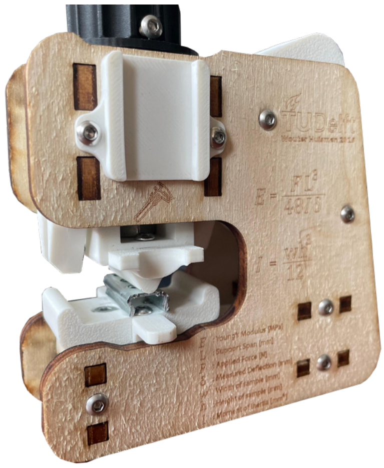


Figure 48. Load Cell Deflection Test

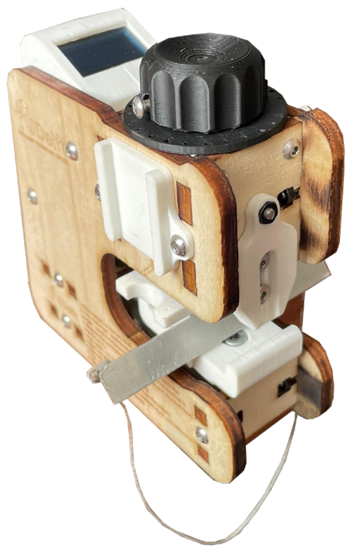


Figure 49. Force Measurement Test

9.2.4 Combined Measurement Uncertainty

To see how these errors add up, an uncertainty propagation was done based on the two main sources:

- ±0.06 mm on each deflection reading
- ±0.05 kg (~±0.49 N) on the force reading
- ±7.5% on the moment of inertia (based on sample geometry measurement using calliper)

The deflection interval (Δd) used in the modulus calculation ends up with a combined uncertainty of ±0.085 mm, which leads to about 8.5% error in the slope itself. When everything's combined, the overall uncertainty in the effective modulus is estimated at ±11.3%. This margin is reasonable for the educational goals of the setup. Full calculation steps are in Appendix I4.

9.2.5 Other Mechanical Factors

Some additional effects were considered, but don't affect the result. The mechanical vernier scale for instance, was never used in the final data collection. It includes deformation from the housing and load cell, which makes it useful for general movement reference but not for accurate measurement. Similarly, load cell deflection (Figure 48),of around 0.1 mm per kg, only impacts readings if deflection is measured with the vernier scale which isn't used in any measurements for the calculations. These effects are described in more detail in Appendix I5 and I6.

9.2.6 Sample Testing and Repeatability

To test performance under real use, four different materials (PMMA, PETG, PVC and PS) were measured with six repeated trials each (Figure 50). Deflection was recorded at 1 mm and 2 mm as usual. The results were also compared with the TU Delft Low-End Tensile Tester (LETT) as a benchmark.

The student-built setup achieved a standard deviation of 6.03%, which is well within acceptable limits (based on the LETT) and noticeably lower than the 9.57% measured using the LETT. This suggests that the setup performs well enough for educational purposes when operated within the controlled range. See Appendix I7 for the full dataset and comparison.

9.2.7 Summary

The mechanical validation confirms that the setup is accurate and reliable enough for its intended context. Deflection and force readings fall within a consistent range, and the combined uncertainty in the modulus calculation remains below ±12% with the tested standard deviation being around ±6%..

Compared to an existing classroom tool (LETT), the setup shows even better repeatability over the 1 and 2 mm slope, meaning the device meets educational requirements . It also avoids the typical risks associated with student-operated tools: it's stable, compact, and straightforward to use. Based on this, the setup meets the technical requirements related to measurement accuracy and repeatability.

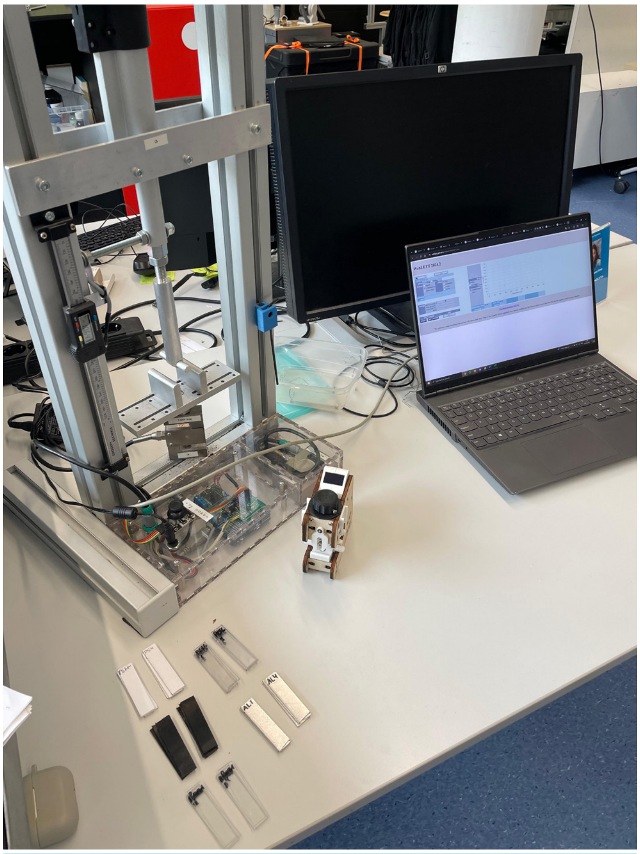


Figure 50. Workshops Timeline

9.3 Assessment on Feasibility, Viability and Desirability

A good design to be feasible, viable, and desirable. This framework, often visualised as the intersection of three overlapping domains (Figure 51), is a core principle in design thinking. Feasibility addresses technical and practical constraints, viability looks at long-term use, cost, and scalability and desirability relates to user needs and learning value. This section evaluates the final setup using those three lenses. Each requirement defined earlier in the project (*Chapter 4*) is addressed here, based on evidence gathered during the final design phase, educational implementation, and mechanical validation. The goal is to determine if the design works and makes sense in its intended educational context.

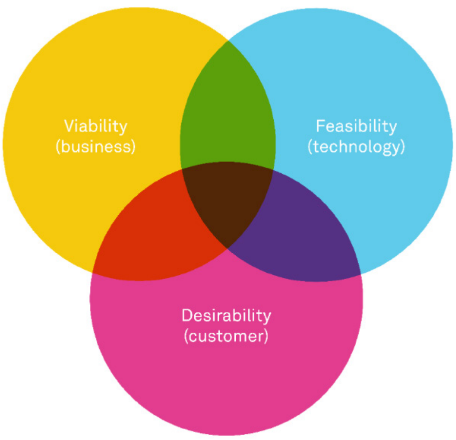


Figure 51. F/V/D framework (Vinney, 2023)

9.3.1 Feasibility

The final device is compact, low-tech, and made from standard components. The frame is laser-cut, internal parts are 3D printed, and all electronics are off-the-shelf (R8, R6). Portability and assembly were confirmed during the implementation phase (R4).

Students were able to use the device during the workshop, but some struggled with sample alignment, calliper placement, or interpreting the force display. This suggests that while R10 is partially met, better instructions or built-in guidance could improve independent usability. Safety was maintained: the force input is manually limited, and the electronics are enclosed (R3). No safety incidents or damage were observed.

Mechanical validation showed that the setup works reliably across test runs. Measurements were repeatable, and no parts failed during testing. The materials used can be reused across sessions, and construction is modular (R9). The structured setup included visual aids and placement icons, partly addressing intuitive use (R17), though several students still missed placement cues or made measurement mistakes. This suggests R17 is not fully met.

The setup uses minimal loose parts and is operated via a single rotating knob, fulfilling R20. It also avoids complex technology and depends only on basic digital feedback, aligning with R11. Components were assembled using accessible tools, and no specialist skills were needed, supporting R6. Maintenance and repairs are straightforward, meeting core aspects of R16.

9.3.2 Viability

Cost analysis shows the setup can be built for €87.91 as a one-off and €39.43 in batches of 75 units, as required for course integration (R19). The device itself costs even less in bulk and remains affordable as a standalone tool.

Setup time during testing consistently remained under five minutes per device, satisfying R5 and supporting efficient workshop flow. No expensive consumables were used, and the test can be repeated without significant material cost, meeting R15. The number of loose or failure-prone parts is limited, supporting ease of maintenance and use (R20).

Though initial results are positive, long-term durability remains uncertain. During testing, the load cell showed signs of flex under repeated load, which could affect reusability over time. This suggests R16 is only partially met and that reinforcement may be needed in future versions.

The setup fits well with the structure and learning goals of the UPE course. It was tested in a full workshop format and supported the type of reasoning the curriculum aims to develop. The course coordinator has expressed to start testing in the course. There are also plans to introduce a new learning objective around scientific measurement, directly influenced by this project. R23 is therefore considered met: the setup is clearly suitable for integration.

On top of meeting the requiremets regarding viability Dr. Calvin Rans (Aerospace Engineering, TU Delft Teaching Lab) expressed strong support for the educational value of the combined intuitive–structured setup. He encouraged engagement with PRIMEC (PRactices In MEChanics) education, a cross-faculty teaching community focused on mechanics education.

Presenting the setup at PRIMEC could attract valuable feedback, institutional interest, and support for broader scaling. If adopted more widely through this network, the setup could transition from a course-specific solution to a reusable platform for hands-on material education across TU Delft and beyond,

9.3.3 Desirability

The final setup supports structured learning about material stiffness while allowing hands-on exploration. Students reported increased understanding of concepts like deflection and stiffness after using the tool. They could connect the experience to the theory introduced later, meeting R1.

The combination of intuitive and structured testing methods gave students a clear pathway from trial to explanation (R2). Immediate feedback was available through the digital display, fulfilling R12, though some students were unsure when to take measurements, suggesting R18 was only partially met. The structured device also enabled structured, reproducible measurement of a clear material property (stiffness via effective modulus) fulfilling R7.

The workshop format supported small group use and active participation (R13). Students interacted directly with the hardware, satisfying R14. The setup followed a Productive Failure structure, where students explored first and then formalised understanding, fulfilling R23. Callipers were used to measure deflection, helping students practice a key engineering skill (R22). Tests were designed to be non-destructive, in line with R21, although some soft materials did deform under repeated use.

9.3.4 Partially Met Requirements

While most requirements were met by the final setup, a few were only partially achieved. These areas are summarised below, including potential improvements for future iterations.

- R7 – Student operation without supervision: Students were able to use the device, but sometimes required help with alignment, reading the display, or knowing when to measure. This suggests that the current setup is close to usable independently but would benefit from clearer instructions or a guided checklist.
- R16 – Long-term durability and maintenance: The modular build supports repair, and components are accessible. However, during mechanical testing, the load cell showed signs of bending under load. This raises concerns about long-term durability and suggests that reinforced or replaceable parts may be needed in future versions.
- R17 – Intuitive guidance through cues: The setup includes some engraved instructions and small icons for placement, but several students still made mistakes during measurement. Current visual cues help but aren't yet strong enough to fully support intuitive use.
- R18 – Clarity of action–result relationship: Students understood that force caused deflection, but several were unsure when to record a measurement. Improving visual or tactile feedback at key points could help reinforce this link more clearly.
- R21 – Non-destructive testing: The test itself is non-destructive in principle, but softer materials did show permanent deformation after repeated use. Future versions could specify material guidelines or limit loading conditions to preserve reusability.

10. Conclusions & Recommendations

10.1 Conclusions

This project set out to design and validate a classroom-ready material testing setup that supports engineering students in developing a deeper understanding of material stiffness through hands-on learning. The context was the Understanding Product Engineering (UPE) course at TU Delft, where current material education is largely theoretical, and opportunities for physical interaction with materials are limited.

Initially, the assignment focused on helping students identify unknown materials. However, early analysis of the curriculum, assessment formats, and stakeholder feedback revealed that students struggled less with recognition and more with interpreting material behaviour. As a result, the goal was refined to focus on supporting structured reasoning about material properties, particularly stiffness.

A dual-track approach was developed: an intuitive track to prompt exploration and engagement, and a structured track to guide students toward accurate measurement and analysis. These tracks were later combined into a single setup and tested in a workshop setting. The workshop was built around the Productive Failure model used in UPE, where students first explore a problem through trial and error before being introduced to relevant theory.

Educational outcomes

User testing showed that the final setup effectively helped students move from intuition to structured reasoning. Students became more confident in their understanding of stiffness and Young's Modulus and could link physical observations to theoretical concepts. The intuitive and structured parts of the workshop played different but complementary roles: the former triggered engagement and comparison, while the latter deepened understanding through measurement and reflection.

Mechanical outcomes

Mechanical testing showed that the structured setup produces repeatable and interpretable measurements. Though the device does not produce textbook material constants, the use of an effective modulus allowed students to compare material behaviour in a controlled, classroom-safe context. The total uncertainty in the calculated modulus was estimated at ±11.3%, with testing of the device coming down to around ±6.3%. The device showed better repeatability over the 1 to 2 mm slope than the LETT, which is promising for meeting educational requirements that have to be defined if the setup is implemented into the course.

Design evaluation

A final assessment using the Feasibility–Viability–Desirability (FVD) framework confirmed that the setup is:

- Feasible: It is compact, safe, easy to build, and reproducible with standard tools and parts.
- Viable: The per-unit cost in bulk production is below €40, and the setup is serviceable and modular.
- Desirable: Students showed increased understanding, and their feedback confirmed that the setup made abstract concepts feel real and accessible.

At the same time, some aspects were only partially met. Students still had some difficulty using the device and the load cell showed signs of bending under repeated use, raising questions about long-term durability.

10.2 Recommendations

The final setup works well and meets the key requirements, but like any design, there's still room to improve. Based on workshop feedback, technical testing, and a few things that showed up during use, several follow-up steps are recommended.

1. Improve the Workshop and Educational Materials

The workshop showed that the setup supports learning in the way UPE aims for, but the structure itself can be refined. Some students weren't exactly sure when and how to take a measurement, which suggests that the instructions need work. A short checklist and a visual guide would go a long way here.

To make the workshop easier to scale up, it would help to finalise the full kit. This includes defining which materials should be included, preparing a standard set of test samples, and creating a basic handout or guide for instructors. Right now, it works, but it still feels like a first draft.

2. Refine the Intuitive Track

The intuitive track got less design attention during the project but deserves a closer look. One example: the conductivity test only tells you whether a material conducts electricity or not. It could be more useful if it gave rough levels like low, medium, or high conductivity.

Other tests, like scratch resistance or thermal feel, could also be improved. Even simple changes, like adding a reference scale or improving the layout, might make them more informative and engaging.

3. Strengthen Technical Reliability

On the technical side, there are a few clear improvements to make. First, the load cell mount needs to be sturdier. During mechanical testing, it has permanently been deformed, which causes the load cell to sit at an angle. It didn't break anything, but it does affect consistency.

There are also the glitches in the force readings. This is likely due to the load cell amplifier and could probably be fixed with a small capacitor or bit of shielding. It's a simple change but would make the output more reliable. Finally, while the device worked fine in short-term use, there hasn't been any real durability testing over time. It's not yet clear how well it will hold up after multiple runs with different student groups. That's something future testing should address.

4. More Testing and Keep Stakeholders Involved

The workshops were tested with a small group of first year IDE students, most of whom already knew a bit about the theory. To get a better sense of how effective the setup really is, it should also be tested with students who haven't seen this material yet. That would give a clearer picture of how much the setup teaches, not just reinforces.

A formal safety review is also recommended. No problems came up during use, and safety has been taken into account while designing the setup, but it should still be properly tested and documented.

Presenting this project at a PRIMEC session is highly recommended. The community brings together educators from across TU Delft who focus on teaching mechanics, making it an ideal platform to showcase the testing setup and its educational potential. A short demonstration could generate valuable feedback, highlight opportunities for cross-faculty adoption, and potentially lead to broader implementation or support. Engaging with PRIMEC would also strengthen the project's alignment with institutional goals for scalable, hands-on engineering education.

11. Reflection

This project didn't always go smoothly. I went through a difficult period personally, and that definitely affected my planning and focus. It was hard to give myself permission to take more time, even when my supervisors told me it was okay. I had this feeling that I had to keep going and deliver on schedule. But eventually, I let that go, and I'm glad I did.

One of the biggest challenges was figuring out what the real problem actually was. I kept circling around it, trying to define something concrete, but it never felt quite right. At my midterm, I was still unsure. What helped was simply sitting down and sketching. It gave me a starting point. From there, the project started to open up. I had something to hold onto. The conversations I had with my supervisors were also a turning point. They helped me zoom out, find perspective, and move forward when I couldn't see the way myself.

In earlier projects, I never had time to improve things after the first real version. There was always a deadline closing in. This time, I made room for a proper second iteration. And I used it. After building the first version, I realised it just wasn't good enough yet. I saw what needed to change, and for once, I actually had the time to do it. So I went back to the start and redesigned it. Completely. That process gave me a strange kind of calm. It made everything click into place. I wasn't just pushing something over the finish line, I was building something I believed in.

But that momentum also came with a downside. After the second iteration, I found it hard to stop. I just wanted to keep going, keep improving, tweaking, rebuilding. It was exciting to finally have the space to iterate properly, and I got caught up in it. Sometimes, that meant I lost track of other things. I kept working, kept adjusting, even when the gains got smaller. That's something I've learned about myself too: knowing when to stop is just as important as knowing how to push forward.

I also surprised myself with how quickly I could pick things up when I needed to. For example, I'd never dealt with measurement uncertainty before. But I dug into it, figured it out in an evening, and applied it to my own setup. And I made it work. That kind of learning gave me confidence, not just in the outcome, but in myself.

Even though the final design feels complete, I know it's not the full answer. It's a strong first stepbut the problem space is bigger, and there's so much more potential left to explore. Still, this result is something I'm proud of. Not just because it works, but because I know what led to it. I know the choices behind it. I know the struggle it came from. And I know, without a doubt, that it's mine.

References

Ansys Inc. (2023). Granta EduPack [Computer software]. https://www.ansys.com/products/materials/granta-edupack

APR Composites. (n.d.). Materials testing and characterisation: Exploring methods and applications. Retrieved May 4, 2025, from https://aprcomposites.com.au/materials-science/materials-engineering/materials-testing-characterization/

Ashby, M. F., Shercliff, H., & Cebon, D. (2009). Materials: Engineering, science, processing and design. Butterworth-Heinemann. ISBN: 9781856178945

ASTM International. (2017). ASTM D790-17: Standard test methods for flexural properties of unreinforced and reinforced plastics and electrical insulating materials. https://www.astm.org/d0790-17.html

Beitz, W., Küttner, K.-H., & Heisel, U. (Eds.). (2010). Springer handbook of metrology and testing. Springer. ISBN: 978-3-642-16640-2

Beer, F. P., Johnston, E. R., DeWolf, J. T., & Mazurek, D. F. (2012). Mechanics of materials (7th ed.). McGraw-Hill Education.

Britannica. (n.d.). Materials testing. Retrieved May 4, 2025, from https://www.britannica.com/technology/materials-testing

Callister, W. D., & Rethwisch, D. G. (2014). Materials science and engineering: An introduction (9th ed.). Wiley. https://archive.org/details/materialsscienceandengineering9thedition/

Callister, W. D., & Rethwisch, D. G. (2020). Materials science and engineering: An introduction (10th ed.). Wiley.

CAMPUS. (n.d.). CAMPUS Plastics Database. Retrieved May 4, 2025, from https://www.campusplastics.com/

Czichos, H., Saito, T., & Smith, L. (Eds.). (2011). Springer handbook of metrology and testing. Springer. ISBN: 978-3-642-16640-2'

Delft University of Technology. (n.d.). Foresight exploration. Delft University of Technology. Retrieved June 10, 2025, from https://www.tudelft.nl/over-tu-delft/strategie/foresight/applying-foresight/foresight-exploration

DutchNews.nl. (2025, March 25). University cuts are hurting NL's reputation, Delft rector says. Retrieved from https://www.dutchnews.nl/2025/03/government-cuts-are-hurting-nls-reputation-delft-rector-says/

Experiential Learning Institute. (n.d.). What is experiential learning? Retrieved May 4, 2025, from https://experientiallearninginstitute.org/what-is-experiential-learning/

Format NDT. (n.d.). Which sectors use non-destructive testing? Format NDT. https://www.formatndt.co.uk/which-sectors-use-non-destructive-testing/

Groover, M. P. (2016). Fundamentals of modern manufacturing: Materials, processes, and systems (6th ed.). Wiley. https://www.wiley.com/en-us/Fundamentals+of+Modern+Manufacturing%3A+Materials%2C+Processes%2C+and+Systems%2C+6th+Edition-p-9781119128793

Groover, M. P. (2016). Fundamentals of modern manufacturing: Materials, processes, and systems (6th ed.). Wiley. ISBN: 9781119128694

GUNT. (n.d.). Mechanical testing methods [PDF]. Retrieved May 4, 2025, from https://www.gunt.de/images/download/mechanical_testing_methods_english.pdf

IDEO.org. (2015). The field guide to human-centered design. IDEO.org. https://www.designkit.org/resources/1
Interface Force Measurement Solutions. (2024, October 10).

Types of Load Cells 101. Retrieved May 4, 2025, from https://www.interfaceforce.com/types-of-load-cells-101/

International Organization for Standardization. (2019). ISO 178:2019 Plastics, Determination of flexural properties. https://www.iso.org/standard/70513.html
Mitutoyo. (n.d.). Digimatic schuifmaat 0–150 mm (Art. no. 500-155-30). Mitutoyo Europe. Retrieved June 4, 2025, from https://shop.mitutoyo.nl/web/mitutoyo/nl_NL/mitutoyo/01.03.06a/Digimatic%20schuifmaat%200-150mm/$catalogue/mitutoyoData/PR/500-155-30/index.xhtml

Mitutoyo. (n.d.). Schuifmaat 0–150 mm, standaard (Art. no. 530-316). Mitutoyo Europe. Retrieved June 4, 2025, from https://shop.mitutoyo.nl/web/mitutoyo/nl_NL/mitutoyo/na/na/PR/530-316/index.xhtml

MFE Inspection Solutions. (2024, November). What is destructive testing? Methods, examples & more [Web page]. MFE Inspection Solutions. https://mfe-is.com/destructive-testing/

Morehouse Instrument Company. (2021, April 26). Types of Load Cells. Retrieved May 4, 2025, from https://mhforce.com/types-of-load-cells/

OECD. (2023). Education at a Glance 2023: Netherlands Country Note. Retrieved from https://www.rijksoverheid.nl/binaries/rijksoverheid/documenten/rapporten/2023/09/12/country-note-education-at-a-glance-2023/country-note-education-at-a-glance-2023.pdf

Pahl, G., Beitz, W., Feldhusen, J., & Grote, K.-H. (2007). Engineering design: A systematic approach (3rd ed.). Springer. https://link.springer.com/book/10.1007/978-1-84628-319-2

Persaud, S., & Flipsen, B. (2023). Productive Failure Pedagogy in Engineering Mechanics. EPDE Conference.

Radboud University. (n.d.). Integrating learning objectives. https://www.ru.nl/en/staff/lecturers/designing-education/designing-courses/integrating-learning-objectives

Radiant Digital. (n.d.). What is iterative design? Radiant Digital. Retrieved June 10, 2025, from https://www.radiant.digital/what-is-iterative-design/

Joint Committee for Guides in Metrology (JCGM). (2008). Evaluation of measurement data — Guide to the expression of uncertainty in measurement (JCGM 100:2008). BIPM. https://www.bipm.org/documents/20126/2071204/JCGM_100_2008_E.pdf

SparkFun Electronics. (n.d.). Getting started with load cells. Retrieved May 4, 2025, from https://learn.sparkfun.com/tutorials/getting-started-with-load-cells/all

Taen, R. (2024). Material behaviour and student reasoning: Improving educational setups in IDE. TU Delft. https://repository.tudelft.nl/record/uuid:a8648cc6-e3b4-4a37-9836-2dae22adab09

Universiteit Leiden. (2025, April 15). Executive Board responds to government cuts. Retrieved from https://www.staff.universiteitleiden.nl/news/2024/09/executive-board-responds-to-government-cuts

van Boeijen, A., Daalhuizen, J., Zijlstra, J., & van der Schoor, R. (2020). Delft Design Guide: Design strategies and methods (2nd ed.). BIS Publishers. ISBN: 9789063695611

Vinney, C. (2023, November 9). Desirability, feasibility and viability diagram: What does it mean? - UX Design Institute. UX Design Institute. https://www.uxdesigninstitute.com/blog/desirability-viability-and-feasibility/

WayKen Rapid Manufacturing. (2023). Types of material testing: What are they and why are they important? Retrieved May 4, 2025, from https://waykenrm.com/blogs/types-of-material-testing/

ZwickRoell. (n.d.). Materials testing. Retrieved May 4, 2025, from https://www.zwickroell.com/industries/materials-testing/

Appendix

Contents

Appendix A - Original Project Brief

DESIGN FOR our future

TU Delft

IDE Master Graduation Project

Project team, procedural checks and Personal Project Brief

In this document the agreements made between student and supervisory team about the student's IDE Master Graduation Project are set out. This document may also include involvement of an external client, however does not cover any legal matters student and client (might) agree upon. Next to that, this document facilitates the required procedural checks:

- Student defines the team, what the student is going to do/deliver and how that will come about
- Chair of the supervisory team signs, to formally approve the project's setup / Project brief
- SSC E&SA (Shared Service Centre, Education & Student Affairs) report on the student's registration and study progress
- IDE's Board of Examiners confirms the proposed supervisory team on their eligibility, and whether the student is allowed to start the Graduation Project

STUDENT DATA & MASTER PROGRAMME
Complete all fields and indicate which master(s) you are in

Family name	Huisman 7487	IDE master(s)	IPD ✓ DfI SPD
Initials	W	2nd non-IDE master	
Given name	Wouter	Individual programme *(date of approval)*	
Student number	5596777	Medisign	
		HPM	

SUPERVISORY TEAM
Fill in he required information of supervisory team members. If applicable, company mentor is added as 2nd mentor

Chair	Erik Tempelman	dept./section	SDE
mentor	Adrie Kooijman	dept./section	SDE
2nd mentor			
client:	Bas Flipsen		
city:		country:	
optional comments	Erik and Adrie expertises within the SDE department differ greatly from eachother. Erik is a materials expert, and Adrie's focus lies on electronics. Both of these areas are very important for my project, so they are both necessary as part of the team.		

! Ensure a heterogeneous team. In case you wish to include team members from the same section, explain why.

! Chair should request the IDE Board of Examiners for approval when a non-IDE mentor is proposed. Include CV and motivation letter.

! 2nd mentor only applies when a client is involved.

APPROVAL OF CHAIR on PROJECT PROPOSAL / PROJECT BRIEF -> to be filled in **by the Chair** of the supervisory team

Sign for approval (Chair)

Erik Tempelman Digitally signed by Erik Tempelman Date: 2024.11.12 14:38:00 +01'00'

Name Erik Tempelman Date 12 Nov 2024 Signature

CHECK ON STUDY PROGRESS

To be filled in **by SSC E&SA** (Shared Service Centre, Education & Student Affairs), after approval of the project brief by the chair.
The study progress will be checked for a 2nd time just before the green light meeting.

Master electives no. of EC accumulated in total		EC
Of which, taking conditional requirements into account, can be part of the exam programme		EC

★	YES	all 1st year master courses passed
	NO	missing 1st year courses

Comments:

Sign for approval (SSC E&SA)

L. Boot Digitaal ondertekend door L. Boot Datum: 2024.12.09 12:27:16 +01'00'

Name L. Boot Date 9 dec 2024 Signature

APPROVAL OF BOARD OF EXAMINERS IDE on SUPERVISORY TEAM -> to be checked and filled in by IDE's Board of Examiners

Does the composition of the Supervisory Team comply with regulations?

YES	★	Supervisory Team approved
NO		Supervisory Team not approved

Comments:

Based on study progress, students is ...

★	**ALLOWED** to start the graduation project
	NOT allowed to start the graduation project

Comments:

Sign for approval (BoEx)

Monique von Morgen Digitally signed by Monique von Morgen Date: 2025.05.12 19:54:29 +02'00'

Name Monique von Morgen Date 12 May 2025 Signature

Personal Project Brief – IDE Master Graduation Project

Name student Wouter Huisman

Student number 5,596,777

PROJECT TITLE, INTRODUCTION, PROBLEM DEFINITION and ASSIGNMENT
Complete all fields, keep information clear, specific and concise

Project title Experiental Determination Station

Please state the title of your graduation project (above). Keep the title compact and simple. Do not use abbreviations. The remainder of this document allows you to define and clarify your graduation project.

Introduction

Describe the context of your project here; What is the domain in which your project takes place? Who are the main stakeholders and what interests are at stake? Describe the opportunities (and limitations) in this domain to better serve the stakeholder interests. (max 250 words)

The "Understanding Product Engineering (UPE)" course within the Industrial Design Engineering program at TU Delft aims to teach students essential engineering knowledge, focusing on maths, physics, material properties, and production methods. This knowledge is important for making informed decisions about material selection and product manufacturing processes in real-world engineering contexts. According to the Onderwijs- en Examenregeling (OER), students must be able to apply these principles to understand and optimize product performance, directly tying material properties to design choices.

While the course introduces these essential principles, they are mostly limited to theory due to time and budget constraints. They do some determination tests during the course, but educators see the need for a new, hands-on and easy to use setup which will, in combination with Granta Edupack (a materials database software), allow students to determine materials. The materials they will encounter will be from a shortlist of often-occurring materials from the design industry and the hope is that this hands-on experience will lead to a better understanding of the theory.

In addition to UPE, there is another mandatory technical course within the bachelor called "Product Engineering (PE)". Students are also able to choose the elective courses "Materials and Manufacturing" and "Design Engineering contest" and/or the minor "Advanced Prototyping" to dive deeper into these engineering subjects. By creating an experiential setup that is more than capable for the requirements of UPE, it could also be used by the more specialist courses to dive even deeper into the subject.

➔ *space available for images / figures on next page*

introduction (continued): space for images

image / figure 1

image / figure 2

Personal Project Brief – IDE Master Graduation Project

Problem Definition

What problem do you want to solve in the context described in the introduction, and within the available time frame of 100 working days? (= Master Graduation Project of 30 EC). What opportunities do you see to create added value for the described stakeholders? Substantiate your choice.
(max 200 words)

This project focuses on improving the limited hands-on tools available to students in the "Understanding Product Engineering" (UPE) course. It is very important for students to be familiar with the material properties of materials they will encounter often as design engineers. They must be able to ensure that the materials chosen will meet the performance, durability and safety requirements of a product under various conditions.

In 100 working days, this project aims to create a setup where students can use three to four low-tech tests, in combination with Granta, to which material a certain sample is. The samples which need to be determined will be taken from a shortlist of materials that are often used in design industry. By combining multiple tests into one setup, students will get hands-on experience with a broader range of material properties, helping them connect what they learn in theory with real, physical examples. This approach is expected to make it easier for them to understand and remember the material.

This project benefits multiple groups. Students gain practical knowledge that prepares them for future engineering work. Professors get a better teaching tool that helps students grasp complex ideas more easily and enjoyably. Additionally, the setup could be used in other courses, like "Product Engineering" and other electives on materials and manufacturing, making it a valuable addition to the department's resources for teaching about materials.

Assignment

This is the most important part of the project brief because it will give a clear direction of what you are heading for. Formulate an assignment to yourself regarding what you expect to deliver as result at the end of your project. (1 sentence) As you graduate as an industrial design engineer, your assignment will start with a verb (Design/Investigate/Validate/Create), and you may use the green text format:

Design an experiential setup which can be used by students to help determing material properties in the 'Understanding Product Engineering' bachelor course.

Then explain your project approach to carrying out your graduation project and what research and design methods you plan to use to generate your design solution (max 150 words)

This project will follow an iterative, hands-on approach, emphasizing the embodiment and testing of prototypes through design sprints to refine the setup. An early prototype will be tested by Bachelor students, to provide feedback on key areas such as ease of use, engagement, durability, educational value, and appropriate challenge level. This hands-on testing will ensure the setup is intuitive, holds students' interest, withstands repeated use, and enhances understanding of material properties in a way that is stimulating but not overwhelming. Using this feedback, the end goal will be developed, a functional prototype along with a basic instruction manual to support teachers with integrating it into courses.

Project planning and key moments

*To make visible how you plan to spend your time, you must make a planning for the full project. You are advised to use a Gantt chart format to show the different phases of your project, deliverables you have in mind, meetings and in-between deadlines. Keep in mind that all activities should fit within the given run time of 100 working days. Your planning should include a **kick-off meeting**, **mid-term evaluation meeting**, **green light meeting** and **graduation ceremony**. Please indicate periods of part-time activities and/or periods of not spending time on your graduation project, if any (for instance because of holidays or parallel course activities).*

Make sure to attach the full plan to this project brief.
The four key moment dates must be filled in below

Kick off meeting	12 Nov 2024
Mid-term evaluation	14 Jan 2024
Green light meeting	11 Mar 2024
Graduation ceremony	8 Apr 2024

In exceptional cases (part of) the Graduation Project may need to be scheduled part-time. Indicate here if such applies to your project

Part of project scheduled part-time	
For how many project weeks	
Number of project days per week	

Comments:

Motivation and personal ambitions

Explain why you wish to start this project, what competencies you want to prove or develop (e.g. competencies acquired in your MSc programme, electives, extra-curricular activities or other).

Optionally, describe whether you have some personal learning ambitions which you explicitly want to address in this project, on top of the learning objectives of the Graduation Project itself. You might think of e.g. acquiring in depth knowledge on a specific subject, broadening your competencies or experimenting with a specific tool or methodology. Personal learning ambitions are limited to a maximum number of five.
(200 words max)

This is a project I'm really drawn to, it's technical and making a viable solution will require going in depth into the subject mater of the project, which is something I really enjoy doing. I've always enjoyed the material selection part of Industrial Design Engineering and this project will allow learn a lot about this subject. Additionally, the project requires a working prototype at the end. Building stuff is something I've enjoyed doing my entire life, but I've often struggled to implement it well during the design process. This individual project is the perfect situation for me to improve that skill.

Competenties I want to prove/further develop:
1. Material Science - properties and the way to test them.
2. Prototyping - properly implemented during the design process.
3. Mechanical Engineering - designing the solution in the proper way.
4. Electronics - arduino, coding, data collection.

Personal goal:
- Improve project management and communication skills by having regular and effective meetings with my chair, mentor and client. A meeting which is properly prepared every time, by means of a short and to the point powerpoint presentation.

Appendix B - Materials, Material Properties and Testing Methods

B1 - Materials Shortlist

Table B1. aterials Shortlist. Source - Data compiled from Callister & Rethwisch (2014), Ashby et al. (2009), CAMPUS (n.d.), and WayKen Rapid Manufacturing (2023).

Material	Type	Why It's Used	Testable Properties
Soda-lime Glass	Ceramic	Cheap and widely available; used in windows and containers.	Transparency, hardness, thermal resistance
Carbon Fiber-Reinforced Polymer (CFRP)	Composite	High strength-to-weight ratio; used in aerospace, sports equipment.	Flexural strength, lightweight
Stainless Steel	Metal	Corrosion-resistant and durable; used in kitchenware, medical devices, and construction.	Corrosion resistance, hardness, density
Aluminum (cast Al-alloys)	Metal	Lightweight and corrosion-resistant; used in transport, packaging, consumer goods.	Density, thermal conductivity, malleability
Copper	Metal	High thermal and electrical conductivity; used in electronics and industrial design.	Conductivity, malleability, thermal properties
Lead	Metal	Dense and malleable; used in radiation shielding and weights.	Density, malleability, thermal conductivity
Iron (cast iron, ductile)	Metal	Durable and strong; used in structural and mechanical applications.	Hardness, magnetic properties, density
Brass	Metal	Corrosion-resistant and malleable; used in fittings, instruments, and decorative applications.	Density, malleability, thermal conductivity
Wood (Oak, Pine)	Natural	Renewable, widely used in furniture and construction.	Grain structure, density, hardness
Bamboo	Natural	Sustainable and durable material for design applications.	Flexibility, density, texture
ABS (Acrylonitrile Butadiene Styrene)	Polymer (Thermoplastic)	Common in 3D printing and consumer products; lightweight, impact-resistant.	Density, hardness, thermal resistance
PVC (Polyvinyl Chloride)	Polymer (Thermoplastic)	Durable and resistant to chemicals; used in pipes and construction materials.	Chemical resistance, density, thermal properties
POM (Polyoxymethylene)	Polymer (Thermoplastic)	High strength, stiffness, and wear resistance; used in gears and mechanical parts.	Hardness, wear resistance, density
PE (Polyethylene)	Polymer (Thermoplastic)	Flexible, lightweight, and chemical-resistant; used in packaging and containers.	Flexibility, chemical resistance, lightweight
PS (Polystyrene)	Polymer (Thermoplastic)	Low cost, lightweight, and rigid; used in packaging and disposable products.	Rigidity, brittleness, density
PETG (Polyethylene Terephthalate Glycol)	Polymer (Thermoplastic)	Versatile, tough, and easily thermoformed; used in packaging and 3D printing.	Transparency, flexibility, thermal resistance
Polylactic Acid (PLA)	Polymer (Thermoplastic)	Biodegradable and used in sustainable product design.	Brittleness, melting temperature, biodegradability
Polycarbonate (PC)	Polymer (Thermoplastic)	Transparent and tough; used in lenses, electronics housings.	Transparency, toughness, thermal properties
PP (Polypropylene)	Polymer (Thermoplastic)	Durable and resistant to fatigue; used in food containers and automotive parts.	Flexibility, fatigue resistance, density
Epoxy	Polymer (Thermoset)	Versatile and strong adhesive; used in coatings, laminates, and electronics.	Adhesive strength, chemical resistance, hardness
Polyester	Polymer (Thermoset)	Durable and versatile; used in textiles, composites, and industrial applications.	Flexibility, thermal resistance, durability

B2 Material Properties Shortlist

Table B2. Material Properties Shortlist - Source: Data compiled from Callister & Rethwisch (2014), Ashby et al. (2009), CAMPUS (n.d.), WayKen Rapid Manufacturing (2023), and Ansys Inc. (2023).

		Material	Sodalime glass	CFRP	Stainless Steel	Aluminium	Copper	Lead	Iron (cast)	Brass	Softwood (vuren)	Hardwood (beech)
		Material Group	Ceramic	Composite	Metal	Metal	Metal	Metal	Metal	Metal	Natural	Natural
Property	Min Value	Max Value										
Mechanical Hardness	1.6 HV	800 HV	650 - 800 HV (6-7 Mohs)	120-160 HV	200-600 HV	60-120 HV	35-45 HV	4-6 HV	200-300 HV	80-200 HV	1.6-2.5 HV	3.2-4.5 HV
Young's Modulus	0.2 GPa	210 GPa	70 GPa	150-200 GPa	190-210 GPa	69 GPa	110-130 GPa	16 GPa	120-170 GPa	96-110 GPa	9-13 GPa	14-18 GPa
Density	0.4 g/cm^3	11.3 g/cm^3	2.5 g/cm^3	1.6 g/cm^3	7.9 g/cm^3	2.7 g/cm^3	8.9 g/cm^3	11.3 g/cm^3	7.2 g/cm^3	8.5 g/cm^3	0.4-0.45 g/cm^3	0.7-0.75 g/cm^3
Electrical Conductivity	0 S/m	5.8 × 10^7 S/m	~0 S/m (Insulator)	1-10 S/m	1.1 × 10^6 S/m	3.8 × 10^7 S/m	5.8 × 10^7 S/m	5 × 10^6 S/m	1.0 × 10^7 S/m	1.5 × 10^7 S/m	~0 S/m (Insulator)	~0 S/m (Insulator)
Corrosion Resistance	Low	Very High	High	Moderate (resin dependent)	Very High	Moderate to High	Low (tarnishes easily)	Low	Low	Moderate	Low (requires treatment)	Moderate (requires treatment)
Thermal Conductivity	0.12 W/m·K	398 W/m·K	1 W/m·K	5-20 W/m·K (anisotropic)	16-25 W/m·K	235 W/m·K	398 W/m·K	35 W/m·K	50-80 W/m·K	109 W/m·K	0.12 W/m·K	0.16 W/m·K
Refractive Index	1.45	1.59	1.51	1.5 (approx, resin dependent)	Opaque (N/A)	Opaque (N/A)	Opaque (N/A)	Opaque (N/A)	Opaque (N/A)	Opaque (N/A)	N/A (opaque)	N/A (opaque)
Melting Point	115 °C	2000 °C	1400°C	Varies (~2000°C for fibers, resin dependent)	1370-1510°C	660°C	1085°C	327°C	1200-1260°C	900-940°C	Combusts ~300°C	Combusts ~300°C
Keep it?												

		Material	Bamboo	ABS	PVC	POM	PE	PS	PETG	PLA	PC
		Material Group	Natural	Polymer TP	Polymer TP	Polymer TP	Polymer TP	Polymer TP	Polymer TP	Polymer TP	Polymer TP
Property	Min Value	Max Value									
Mechanical Hardness	1.6 HV	800 HV	4.5-6.0 HV	110-120 HV	45-50 HV	80-110 HV	10-20 HV	20-30 HV	60-90 HV	60-70 HV	85-110 HV
Young's Modulus	0.2 GPa	210 GPa	10-15 GPa	2.0-2.5 GPa	2.5-3.0 GPa	3.0-3.5 GPa	0.2-0.5 GPa	3.0-3.5 GPa	2.0-2.5 GPa	3.0-3.5 GPa	2.0-2.4 GPa
Density	0.4 g/cm^3	11.3 g/cm^3	0.6-0.8 g/cm^3	1.04 g/cm^3	1.38 g/cm^3	1.41 g/cm^3	0.91-0.96 g/cm^3	1.05 g/cm^3	1.27 g/cm^3	1.24 g/cm^3	1.20 g/cm^3
Electrical Conductivity	0 S/m	5.8 × 10^7 S/m	~0 S/m (Insulator)	~0 S/m (Insulator)	~0 S/m (Insulator)	~0 S/m (Insulator)	~0 S/m (Insulator)	~0 S/m (Insulator)	~0 S/m (Insulator)	~0 S/m (Insulator)	~0 S/m (Insulator)
Corrosion Resistance	Low	Very High	Moderate (depends on treatment)	Very High	Very High	High	Very High	Moderate	High	Moderate	Very High
Thermal Conductivity	0.12 W/m·K	398 W/m·K	0.17 W/m·K	0.17 W/m·K	0.19 W/m·K	0.25 W/m·K	0.22 W/m·K	0.2 W/m·K	0.15 W/m·K	0.13 W/m·K	0.19 W/m·K
Refractive Index	1.45	1.59	N/A (opaque)	1.54	1.54-1.55	1.52	1.51	1.59	1.57	1.45	1.58
Melting Point	115 °C	2000 °C	Combusts ~300°C	220°C (decomposition)	160-210°C	175°C	115°C	240°C	260°C	150-160°C	280-300°C

B3 - Testing Methods Shortlist

Table B3. Testing Methods Shortlist - Source: Compiled from GUNT (n.d.), ZwickRoell (n.d.), and APR Composites (n.d.).

Category	Test Method	Property Tested	Destructive?	Reasoning / Notes
Tactile / Sensory	Scratch Test	Surface hardness	Slightly	Simple, intuitive, useful for early material comparisons
Tactile / Sensory	Magnetic Check	Magnetism	No	Quick check for ferrous vs non-ferrous materials
Tactile / Sensory	Heating Pad Test	Thermal conductivity (feel)	No	Useful for comparing thermal response by touch
Tactile / Sensory	Sound Resonance Test	Acoustic response	No	Hard to interpret, low reliability
Tactile / Sensory	Tactile Weight Judgement	Density (approx.)	No	Highly subjective, inconsistent results
Tactile / Sensory	Flex Test (manual bend)	Flexibility	Yes	Too variable and unmeasurable
Physical / Measured	Archimedes Density Test	Density	No	Reliable, classic method, links to theory
Physical / Measured	3-Point Bending Test	Young's Modulus	No	Clear visual result, safe and educational
Physical / Measured	Tensile Test	Tensile strength	Yes	Requires high forces and safety precautions
Physical / Measured	Drop Test / Impact Test	Toughness	Yes	Destructive and hard to repeat consistently
Physical / Measured	Simplified Vickers Hardness Test	Hardness (quantitative)	Yes	Technical and requires controlled force
Physical / Measured	Ball Indentation Test	Hardness	Yes	Force levels too high for classroom safety
Physical / Measured	Water Absorption Test	Absorption/porosity	Yes	Time-intensive and unclear instructional value
Physical / Measured	Charpy Impact Test	Fracture toughness	Yes	Highly destructive, not safe for unsupervised use
Electrical / Visual	LED Conductivity Test	Electrical conductivity	No	Simple feedback, encourages circuit reasoning
Electrical / Visual	Basic Resistivity Test (2-probe)	Electrical resistivity	No	Requires accurate setup and understanding of Ohm's Law
Electrical / Visual	Multimeter Measurements	Resistivity/voltage	No	Too technical, minimal learning clarity
Visual / Digital	Colour Comparison (Visual ID)	Material classification	No	Very subjective, not property-specific
Visual / Digital	Thermochromic Sticker Test	Thermal reactivity	No	Novel but low educational depth
Visual / Digital	IR Camera Test	Thermal behavior	No	Expensive and abstract, not suitable for teaching
Visual / Digital	Spectroscopy (e.g. FTIR)	Material composition	No	Very precise but a black-box for students
Visual / Digital	Magnetic Density Separation	Density/Magnetism	Yes	Not accurate for precise property measurement

Appendix C - Intuitive v Structured (IvS) User Test

C1 - IvS Full Study

C1.1 Introduction
Following the early technical exploration, two preliminary concept directions were identified:

- Product Pieces (PP): focusing on intuitive, real-world engagement.
- Standardised Material Pieces (SMP): focusing on structured, reproducible testing.
-

At the same time, prior research, including the work of Robin Taen, had highlighted a gap in how students learn about material properties. While hands-on "feel"-based methods promoted engagement and intuitive understanding, they often lacked the reproducibility and analytical rigour required for engineering education. This gap between intuitive and structured learning had not yet been fully explored.

To investigate both the potential of the two concept directions and to address this identified gap, a user test was conducted. It compared two different methods for learning about material hardness:

- A Scratch Test, representing an intuitive, hands-on approach aligned with the Product pieces direction.
- A Simplified Vickers Test, representing a structured, analytical approach aligned with the Standardised Material Pieces direction.

The aim was to understand which method students found more effective, which they preferred, and how each method influenced their understanding of material properties. The results of this test would help inform the concept development and shape the balance between intuitive and structured elements in the final setup.

C1.2 Method

Eleven participants took part in the study, including nine first-year and two second-year IDE students. A short questionnaire was developed to assess their understanding of materials before and after the tests.
The procedure was as follows:

1. Pre-test questionnaire: Students answered questions about their knowledge of material properties, including hardness and magnetism.
2. Scratch Test: This involved students scratching material samples using a steel nail and visually judging the material's resistance to scratching. This test was chosen to represent an intuitive, hands-on method requiring minimal equipment and relying on direct sensory feedback.
3. Simplified Vickers Test: This involved students using a centre punch to create small indentations in the material samples. Students then measured the size of the marks to estimate hardness values. This method introduced a more structured, measurable approach aligned with scientific testing practices.
4. Post-test questionnaire: Students reflected on what they had learned, which test they preferred, and how their understanding of material properties had changed.

C1.3 Results

Performance in the Tests:

- Scratch Test: 3 out of 11 participants correctly identified all materials.
- Simplified Vickers Test: 6 out of 11 participants correctly identified all materials.

While the Scratch Test felt easier and more intuitive for participants, the Simplified Vickers Test produced more accurate and reliable results. This highlighted a clear trade-off between ease of use and scientific precision.

Ease of Understanding and Use:

- Ease of understanding: The Scratch Test received a mean score of 5.0 (very easy to understand); the Vickers Test scored 3.54.
- Ease of use: The Scratch Test scored 4.91; the Vickers Test scored 3.64.

Participants found the Scratch Test quicker and more straightforward to perform, while the Vickers Test required more careful handling and interpretation.

Understanding of Magnetic Properties:
Students also showed knowledge gaps beyond hardness. Only three participants correctly identified steel as a magnetic material, and only one recognised that not all types of steel are magnetic. This suggested a broader issue in understanding fundamental material properties, not limited to hardness alone.

Student Preferences:
While most participants preferred the simplicity of the Scratch Test, 63.6% (7 out of 11 students) recommended the Simplified Vickers Test to fellow students. The reasons cited included its greater reliability, structured nature, and clearer link to scientific measurement practices.

C1.4 Strengths and Limitations

- Clear differences were observed between intuitive and structured approaches.
- The small sample size (n=11) limits the generalisability of the findings.
- The group was mainly composed of first-year students, who may have less developed technical understanding compared to more senior students.
- Self-reported learning might not fully reflect deeper comprehension.
- Comparing two fundamentally different learning approaches (intuitive vs structured) introduced some unavoidable complexity into interpretation.

C1.5 Discussion

The results of this user test suggest that:

- Intuitive testing methods, like the Scratch Test, offer a valuable entry point for engaging students and building early material intuition.
- Structured testing methods, like the Simplified Vickers Test, support more accurate, reproducible scientific learning, although they may be less immediately intuitive.
- Students recognised the value of structured approaches even if they found intuitive methods easier or more enjoyable.
- Knowledge gaps in basic material properties, such as magnetism, were still present despite hands-on activities.

These findings provided important insights into how students interact with different types of testing setups and highlighted the strengths and limitations of intuitive and structured approaches to experiential learning.

C1.6 Conclusions

The exploratory phase helped shape the technical and educational direction of the project. Different materials, properties and testing methods were explored, always with safety, simplicity, and classroom practicality in mind.

The small user test comparing a Scratch Test and a simplified hardness method revealed more than just a preference. While students liked the intuitive, feel-based approach, the structured test gave clearer results and helped them understand the property better. That difference wasn't expected to stand out so clearly, but it did.

It brought up a bigger question: what kind of learning should the setup actually support? Engagement and exploration are clearly valuable, but they don't guarantee understanding. Just giving students hands-on tools isn't enough if they can't interpret what they're doing.
To move forward, the project needed a closer look at the UPE curriculum. What are students expected to learn, and how is that currently taught and assessed? These questions shaped the next phase: a contextual analysis to make sure future design decisions are aligned with actual learning goals.

C2 - IvS Questions and Instructions

Welke vraag wil ik beantwoorden:
"Hoe ervaren studenten het verschil in leerproces, begrip en betrokkenheid tussen een analytische, kwantitatieve en reproduceerbare test en een meer intuïtieve, kwalitatieve benadering?"

Introductie:

Bedankt dat je meedoet aan deze hands-on activiteit! Vandaag gaan we twee tests uitvoeren om de hardheid van materialen te bepalen: een krastest en een vereenvoudigde versie van de Vickers Hardheids test. Deze tests worden vaak gebruikt in de techniek om materiaaleigenschappen te begrijpen, wat essentieel is voor productontwerp.
Het doel is om te vergelijken hoe je deze twee tests ervaart. Ik zal je een paar vragen stellen voor en na de tests om je gedachten te verzamelen over de tests, hoe ze werken en wat je ervan hebt geleerd. Er zijn geen goede of foute antwoorden—ik ben vooral geïnteresseerd in jouw ervaringen en mening. Ook wil ik je vragen om tijdens het uitvoeren van de tests, je gedachtes hardop uit te spreken!

Vragen vooraf:

1 "Kun je uitleggen wat je denkt dat 'hardheid' betekent in de context van materialen?"
(Korte open vraag om te zien wat ze begrijpen.)

2 "Heb je al eens eerder een test gedaan om de hardheid van een materiaal te bepalen? Zo ja, Hoe vaak?"
Nee nog nooit
1-2 keer
3-4 keer
Vaker dan 4 keer

3 "Wat verwacht je te leren van een test zoals de krastest of de Vickers-test?"
(Open vraag om een basis te leggen voor post-test vergelijking.)

4 "Denk je dat een test op basis van observatie (zoals de krastest) makkelijker of moeilijker is dan een test waarbij je berekeningen moet maken (zoals de Vickers-test)? Waarom?"
(Om hun verwachtingen en voorkeuren te begrijpen.)

5 "Kun je bedenken waarom het binnen Industrieel Ontwerpen nuttig is om de harheid van een materiaal te weten?"

Test A Krasproef
Doel: Observeer de hardheid van materialen door samples te krassen.

Stappen:
1. Neem de spijker en kras stevig over elk materiaalmonster met dezelfde druk.
2. Observeer de krasmarkeringen en vergelijk welk materiaal het meest gekrast wordt.
3. Noteer je bevindingen: Welk materiaal was het moeilijkst om te krassen en welk materiaal was het makkelijkst?

Test B Vereenvoudigde Vickers-test
Doel: Meet de hardheid op basis van de grootte van de indrukking.

Stappen:
1. Plaats het sample op een vlakke ondergrond.
2. Zet de centerpons op het sample, en druk er stevig op totdat je een slag voelt.
3. Verwijder de centerpons en meet de diameter van de indrukking met de schuifmaat en het vergrootglas.
4. Bereken de hardhead van het material met de volgende formule:

Hardheid = Kracht / Indrukkingsoppervlak
(ik moet nog even bepalen wat de Kracht van een centerpons is)

5. Noteer je bevindingen voor elk sample en vergelijk.

Vragen achteraf

6 “Hoe goed begreep je de krastest?” Schaal 1-5: 1 = Helemaal niet begrepen 5 = Volledig begrepen
7 “Hoe goed begreep je de Vickers-test?” Schaal 1-5: 1 = Helemaal niet begrepen 5 = Volledig begrepen

Gebruiksgemak:
8 “Hoe gemakkelijk vond je de krastest om uit te voeren?” Schaal 1-5
9 “Hoe gemakkelijk vond je de Vickers-test?” Schaal 1-5

10 “Welke test gaf je een beter inzicht in het concept van hardheid? Waarom?”
(Open vraag om hun leerervaring te beoordelen.)

11 “Vond je het werken met de krastest (intuïtief) makkelijker of moeilijker dan de Vickers-test (analytisch)? Waarom?”

12 “Kun je nu uitleggen wat ‘hardheid’ betekent in de context van materialen?”
(Dit Antwoord kan worden vergeleken met de het Antwoord wat ze voor de rest gaven)

13 “Kun je je nu nog meer redenen bedenken waarom het voor Industrieel Ontwerpers handig is om de hardheid van het materiaal te weten?” (toevoeging op vraag vooraf)

14 “Als je maar één test zou mogen aanbevelen aan een medestudent, welke zou je kiezen: de krastest of de Vickers-test? Waarom?”

C3 - IvS Participant Responses

Participant	1 (loet)	2	3	4	5
1 "Kun je uitleggen wat je denkt dat 'hardheid' betekent in de context van materialen?"	Hoe stevig een materiaal het is, hoe makkelijk het vervormd, hoe snel het breekt.	In Hoeverre een materiaal makkelijk of niet makkelijker vervormbaar is, hoeveel kracht je nodig hebt.	Hoe snel iets beschadigt, bekrast of indeukt. Niet met of iets breekt, maar juist om hoe snel het beschadigt. Het oppervlak.	Hoe hard het materiaal is, hoe makkelijk je er dingen mee kan maken, hoe makkelijk je het kan buigen.	Hoeveel weerstand een materiaal bie tegen dingen zoals krassen, indeuke slijtage. Dus hoe sterk de buitenkant
2 "Heb je al eens eerder een test gedaan om de hardheid van een materiaal te bepalen? Zo ja, Hoe vaak?" **a**.Nee nog nooit **b**.1-2 keer **c**.3-4 keer **d**.Vaker dan 4 keer	B	A	A	A	B
3 "Wat verwacht je te leren van een test zoals de krastest of de Vickers-test?"	Je komt erachter hoe snel het vervormt	Wat geschikte materialen zouden kunnen zijn voor je ontwerp. Wat handig is voor welk doeleinde.	Je krijgt een begrip voor het verschil tussen de materialen. 10x20x of 30x sterker	Aan de ene kant wel, maar door jouw uitleg. Zonder uitleg was dat niet zo gegaan denk ik.	Hoe goed een materiaal tegen krass druk kan en wat dat zegt over de kwa ervan.
4 "Denk je dat een test op basis van observatie (zoals de krastest) makkelijker of moeilijker is dan een test waarbij je berekeningen moet maken (zoals de Vickers-test)? Waarom?"	Ik denk makkelijker, omdat het snel te zien is hoe snel het materiaal veranderd.	In eerste instantie analystisch, maar misschien is gevoel juist wel makkelijker.	, makkelijker zonder metingen	De analytische, omdat het reproduceerbaar is. De andere varieert op gebied van de kracht die jij uitoefend.	Makkelijker, want je ziet meteen wat gebeurt en je hoeft geen ingewikkeld formules te gebruiken.
5 "Kun je bedenken waarom het binnen Industrieel Ontwerpen nuttig is om de harheid van een materiaal te weten?"	Ja het is belangrijk, je moet de eigenschap van een materiaal weten voordat je er mee gaan werken, anders kan het je product kapot maken of het hele nut ervan veranderen. Je moet elke eigenschap van het materiaal weten (kosten, hardheid etc..) Om een goed product te kunnen maken	Als je echt producten gaat ontwerpen ga je wel bepalen wat voor materialen je nodig gaat hebben. Dus het is gewoon handig om dat te weten wat voor krachten het aankan en of het licht of zwaar moet	Materiaalkunde is een hele tak. Gaat niet alleen om gebruik maar ook gewoon om in welke situatie je welk materiaal gebruikt. En sustainability, materialen moeten lang mee kunnen gaan.	Stel je voor je wilt een stijger bouwen, als het dan een heel zacht materiaal is dan zak je er doorheen.	Het is belangrijk omdat je moet wete een materiaal geschikt is voor het ge waarvoor je het wilt ontwerpen, bijvoorbeeld of het slijtvast genoeg i tegen bepaalde krachten kan.
TEST 1	Lood, Messing, Staal, Alu, Koper	Lood, Alu, Messing, Staal, Koper	Lood, Alu, Koper, Messing, Staal	Lood, Alu, Koper, Messing, Staal (subject draait als eerste rondjes)	Lood, Messing, Staal, Alu, Koper
TEST 2	Lood, Alu, Koper, Staal, Messing	Lood, alu, koper, messing, staal.	Lood, Koper, Messing, Alu, Staal	Lood, Alu, Koper, Messing, Staal	Lood, alu, koper, messing, staal.
6 "Hoe goed begreep je de krastest?" Schaal 1-5: 1 = Helemaal niet begrepen 5 = Volledig begrepen	5	5	5	5	5
7 "Hoe goed begreep je de Vickers-test?" Schaal 1-5: 1 = Helemaal niet begrepen 5 = Volledig begrepen	2	4	5	5	4
8 "Hoe gemakkelijk vond je de krastest om uit te voeren?" Schaal 1-5	5	5	5	5	5
9 "Hoe gemakkelijk vond je de Vickers-test?" Schaal 1-5	3	5	03/Jan	4 (als je het vast kan zetten is het makkelijker)	4
10 "Welke test gaf je een beter inzicht in het concept van hardheid? Waarom?"		De eerste geeft me een beter gevoel en inzicht, omdat dingen makkelijk te krassen zijn. De tweede vertrouw ik toch meer. Door de eerste heb je echt door wat hardheid is.	Krastest, het verschil is zo klein dat ik kan haast geen les trekken uit de centerpons test. Er zijn teveel factoren buiten mijn handen om om het nuttig te maken.	De Tweede, Je hebt een reproduceerbare test waarmee je kan vergelijken. Ik denk wel dat het waardevol is om erop te krassen, dan voel je het verschil meer.	De krastest, omdat je direct kunt zien voelen hoe het materiaal reageert. H visueel en tastbaar, wat helpt bij het begrijpen van het concept.
11 "Vond je het werken met de krastest (intuïtief) makkelijker of moeilijker dan de Vickers-test (analytisch)? Waarom?"	De tweede test was meer reproduceerbaar.	De tweede is beter, dat zou ik meer vertrouwen. Duurde niet heel veel langer en was niet echt moeilijk.	Makkelijker, een holbewonerbrein kan ook gewoon krassen. Bij die andere test moet je overal over nadenken of je wel goed meet etc.	Krassen.	De krastest was makkelijker. Het is s en snel te doen zonder dat je ingewik stappen hoeft te volgen.
12 "Kun je nu uitleggen wat 'hardheid' betekent in de context van materialen?"	De tweede test heeft voor mij meer toegevoegd aan de betekenis in mijn hoofd, maar de betekenis is wel hetzelfde gebleven	Ja, Hoe erg iets slijt. Dat zie je heel erg met het erin krassen, het wordt echt dunner.	Nee, Ik denk wel dat ik heb gemerkt dat het veel lastiger is om te meten dan ik dacht. Ik dacht dat er een groter verschil zou zijn.	Hetzelfde	Ja, ik denk dat ik het nu beter begrijp. Hardheid gaat erom hoe goed een materiaal bestand is tegen slijtage of beschadigingen, zoals krassen en de
13 "Kun je je nu nog meer redenen bedenken waarom het voor Industrieel Ontwerpers handig is om de hardheid van het materiaal te weten?"	Nogsteeds redelijk hetzelfde	Misschien iets met de slijtage, hoe lang een product meegaat. Ik zat eerst te denken aan krachten, maar nu ook aan slijtage.	Ik denk dat het vanuit een meer wetenschappelijke mindset een toevoeging is om de aanname te bevestingen. Je kan wel zeggen staal is de beste optie, maar waarom dan?	Als je producten maakt dan wordt dat natuurlijk gebruikt, er kunnen dingen met het materiaal gebeuren, zoals krassen of slijtage. Dat beinvloed de levensduur van het product, dus daar kan je dan rekening	Ja, bijvoorbeeld om te bepalen of ee product geschikt is voor bepaalde omgevingen, zoals buiten, waar mee slijtage of beschadigingen kunnen optreden.
14 "Als je maar één test zou mogen aanbevelen aan een medestudent, welke zou je kiezen: de krastest of de Vickers-test? Waarom?"	De tweede, meer accuraat en consistent.	De tweede, meer betrouwbaar.	Krastest, simpeler Ik heb er meer van geleerd, ook leuker. Dat is verandert van wat ik eerst dacht.	De analytische test, omdat je dan met getalletjes werkt, dat is in de wetenschap beter. Dat geeft een beter beeld dan wanneer je het op gevoel moet doen. Twee mensen kunnen heel anders	De krastest, omdat het eenvoudiger sneller uit te voeren is. Het geeft een goede eerste indruk van de hardheid

	6	7	8	9	10	11
edt n of blijft.	Het heeft te maken met hoe moeilijk het is om een materiaal te veranderen of te beschadigen, bijvoorbeeld door er op te drukken of erover te schuren.	Hoeveel kracht een materiaal aankan voordat het begint te vervormen of kapotgaat, vooral aan de buitenkant.	Hoe stevig de structuur van het materiaal is, en of je er makkelijk in kan snijden, krassen of deuken kan maken.	Hoe hard een materiaal aanvoelt en hoe goed het weerstand biedt tegen dingen zoals druk of scherpe voorwerpen.	Het zegt iets over hoe goed een materiaal zijn vorm behoudt als er druk op wordt uitgeoefend of als het wordt geraakt.	Hoe sterk en duurzaam een materiaal is, met de focus op hoe goed het bestand is tegen beschadigingen aan het oppervlak.
	B	A	A	B	A	B
en of liteit	Of een materiaal geschikt is voor een specifieke toepassing, bijvoorbeeld als je iets stevigs nodig hebt of juist iets dat buigzaam is.	Het helpt om te snappen hoe materialen zich gedragen onder druk of bij beschadigingen, en wat de limieten zijn.	Hoe een materiaal reageert op kracht en hoe dat verschilt van andere materialen, zodat je ze beter kan vergelijken.	Of een materiaal duurzaam genoeg is en of het de juiste keuze is voor een project waar slijtage een rol speelt.	Hoe de structuur van een materiaal invloed heeft op hoe makkelijk het beschadigt of vervormt.	Of een materiaal tegen dagelijkse slijtage kan, en hoe je dat kan toepassen in praktische ontwerpen.
er e	Observatie is makkelijker, omdat het sneller gaat en je niet hoeft na te denken over meetapparatuur of berekeningen.	Berekeningen zijn moeilijker, omdat je precies moet weten wat je doet, terwijl observatie meer een kwestie is van kijken en vergelijken.	Observatie is makkelijker, maar minder precies. Met berekeningen weet je zeker dat de resultaten kloppen.	Observatie is makkelijker te begrijpen, vooral als je geen ervaring hebt met formules en getallen.	De krastest is makkelijker, want je kunt het met je ogen beoordelen zonder complexe apparatuur.	Berekeningen maken is lastiger, want je moet de formules goed begrijpen. Bij een observatie zie je het resultaat meteen.
n of ebruik s of	Als je niet weet hoe hard een materiaal is, kun je iets ontwerpen dat snel stukgaat of niet veilig is. Het is dus nodig om te begrijpen hoe het zich gedraagt onder belasting.	Omdat hardheid helpt te bepalen hoe duurzaam een product is en of het bestand is tegen slijtage of beschadigingen tijdens gebruik.	Het is nodig voor het kiezen van het juiste materiaal, vooral als je iets maakt dat zwaar belast wordt of lang moet meegaan. Je voorkomt fouten in je ontwerp.	Je wilt zeker weten dat het materiaal dat je kiest geschikt is voor de omgeving waarin het wordt gebruikt, zoals buiten waar er veel slijtage of schade kan ontstaan.	Als een product gemaakt is van een te zacht materiaal, kan het sneller kapotgaan of minder veilig zijn. Daarom is het handig om de hardheid te weten.	Het zorgt ervoor dat je ontwerpen betrouwbaar en veilig zijn, en dat ze hun functie goed blijven uitvoeren zonder snel kapot te gaan.
	Lood, Alu, Messing, Staal, Koper	Lood, Alu, Koper, Messing, Staal	Lood, Messing, Staal, Alu, Koper	Lood, Alu, Messing, Staal, Koper	Lood, Alu, Koper, Messing, Staal	Lood, Messing, Staal, Alu, Koper
	Lood, Koper, Messing, Alu, Staal	Lood, Alu, Koper, Messing, Staal	Lood, Alu, Koper, Staal, Messing	Lood, alu, koper, messing, staal.	Lood, alu, koper, messing, staal.	Lood, Koper, Messing, Alu, Staal
	5	5	5	5	5	5
	3	4	2	3	4	3
	5	4	5	5	5	5
	3	4	2	3	5	4
n en et is	De tweede test. Het is preciezer en geeft een duidelijker resultaat dat je echt kunt gebruiken voor vergelijkingen. Maar de krastest maakt het wel makkelijker om snel een idee te krijgen.	De krastest, want het geeft een intuïtief gevoel van hoe hard het materiaal is. Je ziet meteen het effect, terwijl de berekeningen van de tweede test wat abstracter zijn.	De tweede test. Het voelt betrouwbaarder, omdat het resultaat niet afhangt van hoe hard je zelf iets doet. Het is handig om op die manier materialen te vergelijken.	De krastest. Het is minder technisch en meer praktisch. Je ziet direct het effect en snapt daardoor sneller wat hardheid inhoudt.	De tweede test, omdat het een precieze meting geeft die je echt kunt gebruiken. Maar de krastest helpt om het concept van hardheid te visualiseren.	De tweede test. Het geeft een objectieve manier om materialen te vergelijken, wat bij ontwerpen belangrijk is. De krastest is goed om een eerste indruk te krijgen.
simpel kelde	De Vickers-test was analytisch duidelijker en betrouwbaarder, maar de krastest voelde intuïtiever omdat je meteen het effect ziet.	De krastest was makkelijker, want je hebt geen formules of metingen nodig. Je ziet direct wat er gebeurt.	Ik vond de Vickers-test makkelijker, omdat je precies weet wat je doet. De krastest hangt te veel af van hoe hard je zelf iets doet.	De krastest, omdat je het sneller begrijpt en direct een resultaat hebt. Het is minder technisch dan de Vickers-test.	De Vickers-test, omdat het resultaat preciezer is en je minder afhankelijk bent van je eigen inschattingen. Het voelde professioneler.	De krastest was intuïtiever. Het is een directe manier om hardheid te testen, zonder al te veel stappen of berekeningen.
s uken.	Ja, hardheid betekent hoe resistent een materiaal is tegen vervorming of beschadiging, vooral aan het oppervlak. Beide tests hielpen om dat duidelijker te maken.	a, het heeft te maken met hoeveel kracht een materiaal aankan voordat het zichtbaar verandert, zoals krassen of deuken.	Ja, hardheid draait om hoe stevig en duurzaam het materiaal is tegen externe invloeden, zoals krassen of druk. Ik snap nu ook dat het meten van hardheid preciezer is dan ik eerst dacht.	Ja, het zegt iets over hoe goed een materiaal zijn vorm behoudt als er kracht op wordt uitgeoefend. Ik begrijp nu dat het een belangrijke eigenschap is voor verschillende toepassingen.	Ja, het gaat over hoe goed een materiaal weerstand biedt tegen beschadiging. De Vickers-test gaf me een beter beeld van hoe je dat precies meet.	Ja, hardheid is hoe goed een materiaal zich verzet tegen dingen zoals krassen, slijtage en vervorming. Het testen heeft dat inzicht duidelijker gemaakt.
n r	Het kan helpen bij het kiezen van materialen die langer meegaan, vooral als het product veel gebruikt of belast wordt. Duurzaamheid speelt een grote rol.	Het is handig om te weten hoe een product eruit blijft zien na verloop van tijd. Een harder materiaal kan beter bestand zijn tegen dagelijkse slijtage en daardoor langer mooi blijven.	Zeker, als je een product ontwerpt dat met andere harde oppervlakken in aanraking komt, is het belangrijk te weten of het materiaal daardoor beschadigd raakt.	Het helpt bij het ontwerpen van veilige producten, bijvoorbeeld als een product stevig genoeg moet zijn om niet door te buigen of te breken.	Het is ook nuttig om te weten als je een materiaal moet combineren met andere materialen. Als een materiaal te zacht is, werkt het misschien niet goed samen met een harder materiaal.	Ja, bijvoorbeeld om het juiste materiaal te kiezen voor producten die onder zware omstandigheden worden gebruikt, zoals gereedschappen of machines.
en .	De Vickers-test, omdat het preciezer is en je resultaten kunt vergelijken. Dat maakt het beter geschikt voor serieuze ontwerpen.	De krastest, want het is intuïtief en makkelijker te begrijpen. Vooral voor beginners is het een goede manier om hardheid te leren kennen.	De Vickers-test, omdat het betrouwbaarder is en je precies weet hoe hard het materiaal is. Dat is belangrijk voor het kiezen van het juiste materiaal.	De krastest, omdat je er snel mee aan de slag kunt en direct resultaat ziet. Voor praktische inzichten is dat vaak genoeg.	De Vickers-test, omdat het analytischer is en je objectieve resultaten geeft die je echt kunt gebruiken in het ontwerpproces.	De Vickers-test, want het is professioneler en geeft een nauwkeurig inzicht in hoe materialen zich gedragen onder druk.

C4 - IvS Consent Form

TU Delft – Informed Consent Formulier

Titel van het Onderzoeksproject:
Vergelijking tussen Intuïtieve en Analytische Leermethoden bij Hardheidstesten van Materialen

Onderzoeker:
Wouter Huisman, MSc Integrated Product Design, TU Delft
w.huisman-1@student.tudelft.nl

Informatie voor de Deelnemer

Je wordt uitgenodigd om deel te nemen aan een onderzoek naar hoe studenten verschillende soorten leerervaringen ervaren tijdens het testen van materiaaleigenschappen. Het doel is om te onderzoeken hoe intuïtieve (bijv. kraspoef) en gestructureerde (bijv. vereenvoudigde Vickers-test) benaderingen bijdragen aan het begrijpen en interpreteren van hardheid als materiaaleigenschap.

Tijdens de sessie voer je twee korte tests uit en word je gevraagd om kort te reflecteren op je ervaring met beide methoden. Er volgt een kort interview waarin je wordt gevraagd naar je leerervaring en voorkeuren.

De totale duur van je deelname is ongeveer 20–30 minuten. Je bent vrij om vragen over te slaan en mag op elk moment stoppen met het onderzoek, zonder opgaaf van reden.

Er worden geen persoonsgegevens verzameld zoals je naam of contactgegevens. Alle antwoorden worden anoniem en veilig opgeslagen. De resultaten kunnen worden gebruikt voor academische publicaties, onderwijsdoeleinden of toekomstig onderzoek, in lijn met de ethische richtlijnen van de TU Delft.

Alle testmaterialen zijn vooraf getest en veilig bevonden voor gebruik door studenten. De activiteiten worden begeleid en er worden duidelijke instructies gegeven.

Bij vragen kun je contact opnemen met:
Wouter Huisman

Toestemming

☐ Ik heb de informatie hierboven gelezen en begrepen.

☐ Ik geef vrijwillig toestemming om deel te nemen aan dit onderzoek.

☐ Ik begrijp dat ik op elk moment kan stoppen zonder opgaaf van reden.

☐ Ik geef toestemming dat geanonimiseerde gegevens uit dit onderzoek gebruikt mogen worden voor wetenschappelijke publicaties, onderwijs en toekomstig onderzoek.

☐ Ik geef toestemming dat mijn geanonimiseerde gegevens gearchiveerd mogen worden voor onderzoeks- en onderwijstoepassingen.

Naam deelnemer: ______________________

Handtekening: ______________________

Datum: ______________________

Verklaring Onderzoeker

Ik, ondergetekende, bevestig dat ik het onderzoek duidelijk heb toegelicht en eventuele vragen naar beste kunnen heb beantwoord.

Naam onderzoeker: ______________________

Handtekening: ______________________

Datum: ______________________

Appendix D - Intuitive Track (IT)

D1 Intuitive Track Process

D1.1 Goals

The Intuitive Testing Track was developed to support the early stages of learning about materials, especially for students with limited prior knowledge or hands-on experience. The setup needed to:

- Help students recognise and compare basic material behaviours (e.g. conductivity, hardness, density) through direct interaction.
- Lower the barrier to engagement, using simple tools that require little to no explanation.
- Encourage curiosity and discussion by making the differences between materials physically noticeable.
- Be safe, robust, and easy to use independently, so it could fit into existing workshops without extra supervision.
- Avoid overwhelming students with numbers or abstract concepts — the goal was awareness first, not calculation.

D1.2 Ideation

Most test ideas emerged gradually during early research. The focus was always on low-tech, hands-on interactions that felt intuitive.
As the list grew, the ideas were clustered and filtered using a simplified mind-mapping method based on the Delft Design Guide (van Boeijen, Daalhuizen, Zijlstra, & van der Schoor, 2020). This helped remove overlap and compare options against the six Main Drivers. Concepts that were too complex, fragile, or hard to explain were dropped.
The remaining ideas shared a few traits: physically clear, safe to use, and likely to trigger reflection. These formed the shortlist for further evaluation. The full selection process and some sketches are included in Appendix D2.1.

D1.3 Evaluation

The concepts in the intuitive track were assessed using only the drivers relevant to that track: sensory engagement, real-world link, practicality in short sessions, and safety. These criteria reflect the goal of creating low-barrier, hands-on tools that build material intuition through direct interaction. Scientific precision and formal reproducibility, while important elsewhere, were not used as selection criteria here.

- LED conductivity test
- Scratch test
- Sound Resonance
- Heating pad test
- Archimedes density test

The complete evaluation matrix with individual justifications is included in Appendix D2.2.
Table 1 Intuive Track Evaluation Table

Concept	1. Engagement	2. Sensory Intuition	3. Real-World Link	4. Practicality	5. Safety
LED conductivity test					
Scratch test					
Magnetism test					
Heating pad test					
Archimedes density test					
Flex-by-hand test					
Smell test					
Friction ramp					
Weight guessing game					

D1.4 Prototyping

The Intuitive Track prototypes were built to support quick, feel-based testing, not precise measurement. The goal at this stage wasn't to develop polished tools, but to check whether each interaction was understandable, safe, and meaningful in a classroom context. Each of these prototypes was made to be used in upcoming user sessions. The idea is to test whether the interaction makes sense, whether students get the right kind of feedback, and whether the tests actually support the kind of learning this track aims to offer.

The tools are deliberately kept simple. That way, it's easier to make changes based on what comes out of the testing phase. For now, they just need to be functional, understandable, and robust enough to be passed around during a workshop.
Possible versions of each test were sketched out during the concept phase. These sketch explorations were used to weigh options and quickly assess which direction to prototype. The sketches are included in appendix D2.3

The five tests used in this track are:
LED Conductivity Test
A 3D-printed housing holds two prongs, wired to an LED, resistor and battery. If a material conducts, the LED lights up. A strip of sandpaper is included to encourage polishing oxidised or dirty surfaces before testing.
(See Image X)

Scratch Test
A basic scratching pen with a hard tip. There's no real design behind this, it's a single part added to the set. Still, it allows for a clear and direct interaction.
(See Image X)

Sound Resonance Test
A simple spoon. There's again no real design behind this.(See Image X)

Heating Pad Test
A 3D-printed base houses a small heating element, controlled by a boiler-style thermostat that stabilises at around 40°C. Cables are short and clearly routed. PLA was used for the housing, which should hold up fine at this temperature.
(See Image X)

Archimedes Density Test
This test builds on the 1kg scale already used in the course. A container of water is placed on the scale, and the Product Piece is lowered into it using a basic holding mechanism. The goal is to keep the sample fully submerged without adding too much extra volume, as that would affect the measurement.
For now, a simple vertical clip-on arm is used to grab the sample from the top and hold it underwater. This version works well enough for initial testing and student interaction. The holding mechanism will be optimised later to reduce displaced volume and improve accuracy.
(See Image X)

D1.5 User Testing

To evaluate how the intuitive tools supported early understanding of material properties, eight first-year IDE students performed five hands-on tests using a set of standard material samples. Before and after the session, they reflected on their confidence, expectations, and learning experience.
The goal was to see whether simple, sensory-based interactions could help students recognise and compare properties like conductivity, hardness, and density, and whether these experiences supported intuitive material reasoning. The full user test study with appendices can be found in Appendix D3.

Conclusions

The intuitive tests successfully helped students build early awareness of material properties through direct interaction. Although the tools didn't provide quantitative data, they gave students a clearer "feel" for how different materials behave and how those behaviours relate to design considerations.
Key takeaways:

- Improved confidence and engagement: Students felt more confident identifying materials after the session. The average confidence score increased by one point, and many commented that the tests helped them connect theory to sensory input.
- Most effective tests: The scratch test and heat conduction test were consistently identified as the clearest and most intuitive. They offered immediate feedback and sparked discussion.
- Conceptual shifts: The density test prompted students to rethink assumptions like "heavier means denser." Others began to question beliefs like "all metals are hard."
- Limitations of certain tools: The resonance test was harder to interpret. Many students weren't sure what to listen for or how to compare the sounds, making it less reliable than other tests.
- Value of combined feedback: Students found that using multiple simple tests together provided a more accurate picture than relying on one method alone.

Overall, the tests supported the goal of the intuitive track: giving students a fast, accessible starting point for thinking critically about material behaviour. Their responses confirmed that low-barrier, feel-based testing can serve as an effective foundation for deeper learning.

D1.6 Iteration Changes – Intuitive Track

The intuitive tools needed only minor changes after user testing. Most updates focused on improving clarity, usability, and classroom suitability. Details of each update, including sketches, early versions, and technical justifications, are included in Appendix D2.4.

Key changes included:

- Removal of the Sound Resonance Test

Dropped due to consistent confusion during testing. The test didn't add meaningful value and was removed to simplify the set.

- Reintroduction of the Magnet Test

Re-added after students showed persistent misconceptions about magnetism. A basic neodymium magnet reliably challenged these assumptions and supported material reasoning.

- Instruction Plates

Laser-engraved guidance plates were added to the LED and heating pad tools to support independent use.

- USB-C Power Supply

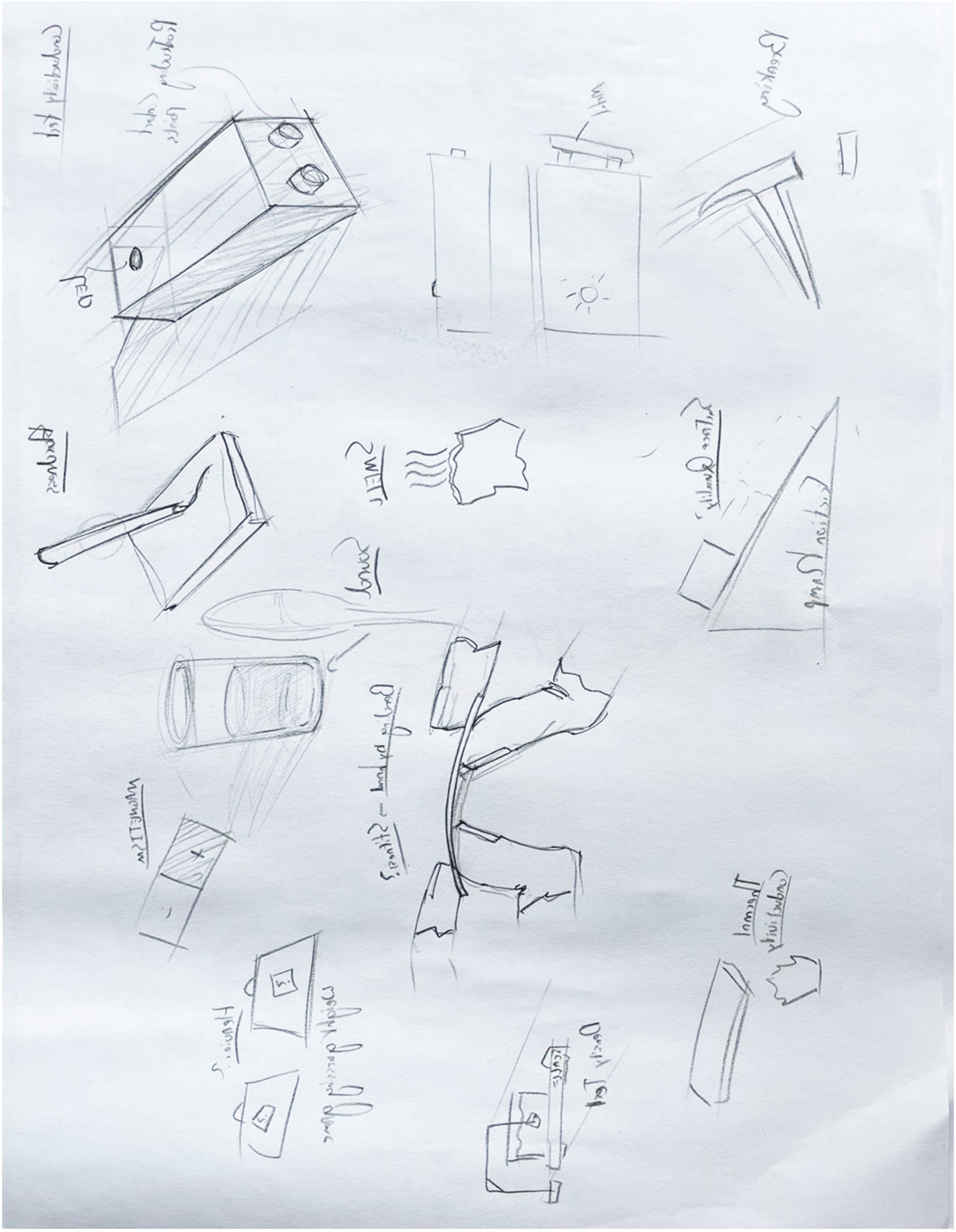
Both electronic tools now use USB-C, improving compatibility and removing the need for batteries.

- Finalised Density Tool

Precision tweezers were added to hold submerged samples with minimal displaced volume, improving measurement accuracy.

D2 Intuitive Track Appendix

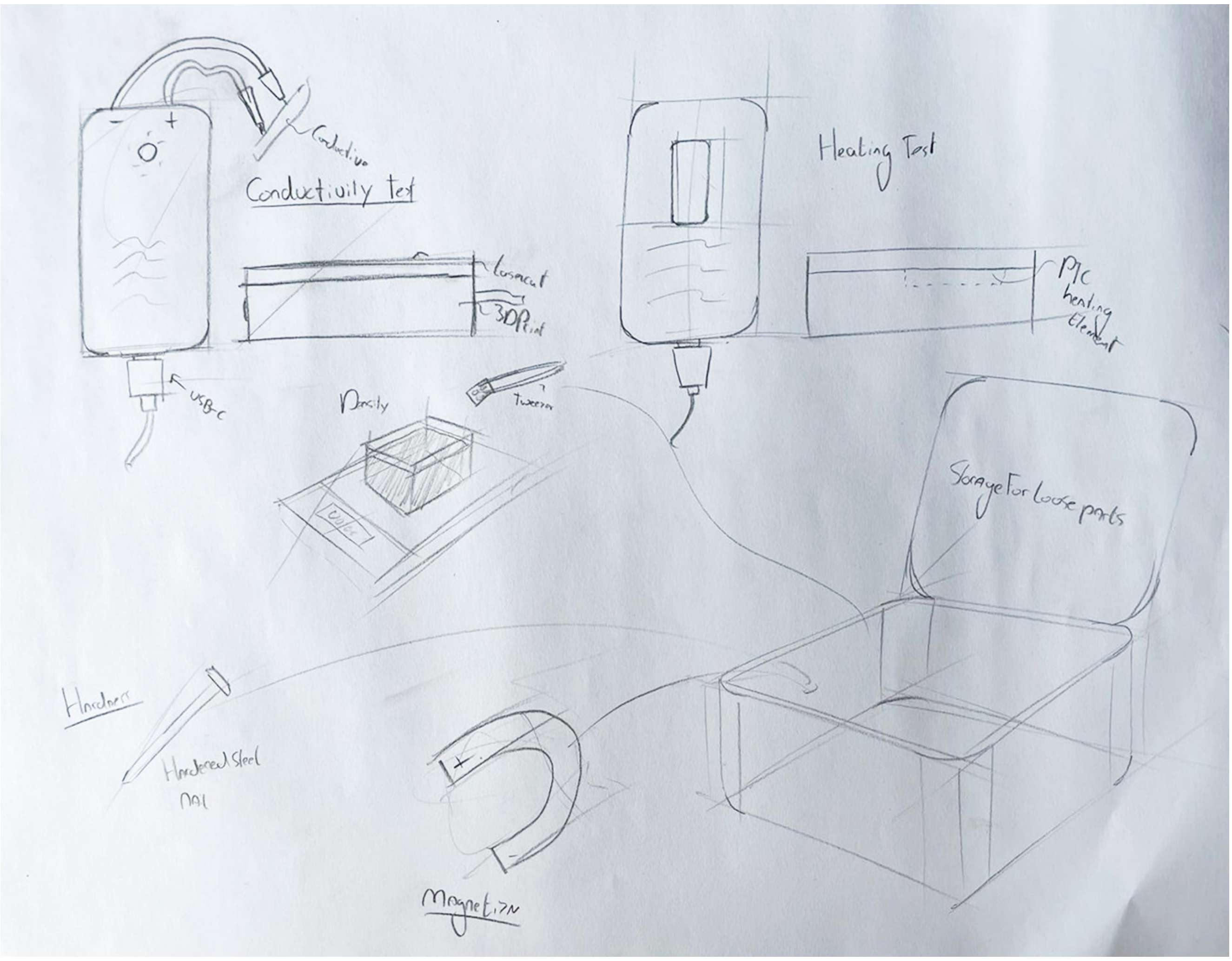
D2.1 – Ideation Sketches



D2.2 - Evaluation Matrix

Concept	1. Engagement	2. Sensory Intuition	3. Real-World Link	4. Practicality	5. Safety	Outcome
LED conductivity test	High – direct cause-effect, students see results immediately	High – strong visual and tactile cue from LED activation	Moderate – connects to basic electronics and materials	High – simple, durable, easy to run repeatedly	High – low voltage, no hazard risk	Selected
Scratch test	Moderate – tactile but brief	High – clear physical contrast across surfaces	Moderate – surfaces relate to wear and finish in design	High – minimal setup, fast comparison	High – safe, uses basic classroom materials	Selected
Magnetism test	High – playful, surprising, and physically engaging	Moderate – magnetic feel is intuitive but lacks nuance	High – strong functional link to product materials	High – no reset, robust components	High – sealed magnets pose minimal risk	Selected
Heating pad test	High – warm touch draws attention and curiosity	High – thermal feedback directly linked to material	Moderate – tied to comfort, safety, and usability	Moderate – needs control of temperature, some setup	High – surface-limited warmth, safe temperatures	Selected
Archimedes density test	High – visible, physical interaction sparks interest	High – buoyancy creates obvious, visual differences	High – directly reflects material density in design	Moderate – involves water, cleanup needed	High – water only, no sharp edges or force	Selected
Flex-by-hand test	Moderate – repetitive motion, less stimulating over time	Moderate – basic force feedback, lacks variation	Moderate – relates to stiffness but lacks control	High – easy to perform but limited feedback	High – low force, safe to use	Rejected
Smell test	Low – limited reaction, not engaging for all students	Low – inconsistent and often imperceptible	Low – minimal design relevance, mostly incidental	High – quick, but unclear outcomes	Moderate – potential allergies or discomfort	Rejected
Friction ramp	High – dramatic but chaotic, hard to repeat fairly	Moderate – some tactile input but difficult to read	High – relates to friction but lacks standardisation	Low – setup and calibration are time-consuming	Moderate – drop hazard or fast movement risk	Rejected
Weight guessing game	Moderate – fun but lacks depth or learning value	Moderate – relies on guesswork more than sensory input	Low – vague link to actual design applications	High – easy to run, but educational value is low	High – no physical risk, low-intensity activity	Rejected

D2.3 - Prototyping



D2.4 - Iteration Changes

The intuitive tools required fewer changes than the structured setup, but several small improvements were made to increase clarity, usability, and classroom feasibility. These updates were based on early user testing and informal evaluations, and were focused on removing confusion, improving consistency, and preparing the set for practical course use.

Removal of Sound Resonance Test
The sound resonance test was dropped entirely based on user testing. Students consistently found it unclear and difficult to interpret, and it didn't contribute meaningful learning value. Removing it simplified the overall set and allowed more time to be spent on tools that gave clearer feedback.

Reintroduction of Magnet Test
The magnet test was added back into the final set. It had been left out during prototyping but was reintroduced after early testing showed that many students still misunderstand magnetism. The tool itself is simple, just a standard neodymium magnet, but it reliably challenges assumptions (e.g. that all metals are magnetic), reinforcing product-level material understanding (see Figure D.x).

Instruction Plates on Tools
Laser-engraved wooden instruction plates were added to the LED conductivity and heating pad tools, where a housing allowed it. These plates provide on-tool guidance, improving usability during independent student work without needing printed instructions or additional supervision (see Figures D.x and Figure D.x).
Tools without housings (scratch, magnet, and density tests) were not fitted with engraved plates, to maintain sourcing flexibility and avoid over-constraining their form.

Power Supply Update (USB-C)
Both the LED and heating pad tools were switched from battery-powered to USB-C input. This makes the setup easier to maintain, eliminates the need to replace or recharge batteries, and aligns better with standard classroom tech (e.g. charging bricks).

Finalised Density Tool with 3D-Printed Tweezers
The density test was finalised using a 3D-printed tweezer tool to hold the sample underwater. This replaces the earlier hook concept and was chosen to minimise displaced volume while improving grip stability.
The kitchen scale used reads to 0.1 g, which equals 0.1 cm^3 of displaced water, so reducing the tweezers' submerged volume directly improves result accuracy (see Figure D.x).

D3 – Intuitive Track User Study

D3.1 – IT Full Study

D3.1.1 Introduction

This study examines how students differentiate materials using simple, sensory-based tests—without lab equipment or detailed theory. The focus is on intuition: weight, feel, temperature, and sound. For many students new to material science, these first impressions are all they have. The question is, can these intuitive tests lead to real understanding?

D3.1.2 Methods
Nine students from TU Delft participated in this study. Each performed a series of five qualitative tests: electrical conductivity, scratch resistance, sound resonance, heat transfer, and density (water displacement). No precise measurement tools were used; the aim was to explore materials through observation and touch. Before testing, students shared their expectations and confidence levels. After each test, they recorded what they observed and whether it matched what they expected. At the end, they reflected on their learning experience and whether their confidence had changed. All questions, their answers and the informed consent form can be found in Appendices D3.2 through D3.4.

D3.1.3 Results

Students initially relied heavily on feel, weight, and temperature to guess material properties. Confidence before the test was generally low to moderate (2–3 out of 5). The hands-on phase gave them a chance to test those assumptions, and for many, it changed their understanding.

Main takeaways:

- Heat transfer and scratch resistance were the clearest and easiest for students to interpret.
- The density (water displacement) test was the most surprising. Many expected heavier materials to be denser, but results challenged that idea.
- Resonance was often described as vague or hard to assess without more guidance.
- Most students reported increased confidence after the full test sequence.
- Several key misconceptions were corrected:

“Metals are always hard.”
“Heavy materials are always dense.”
Representative student quotes:

- “Lood was veel zachter dan ik had verwacht.”
- “Acryl leek zwaar, maar verplaatste veel water — dus toch niet zo dicht.”
- “Je denkt dat gewicht alles zegt, maar dat klopt echt niet altijd.”

D3.1.4 Strengths and Limitations

Strengths:

- Low-barrier setup encouraged active participation and open observation.
- The use of common materials made the activity relatable and replicable.
- Open-ended questions provided rich insights into student thinking and reflection.

Limitations:

- Small sample size (n=9) limits generalization of results.
- No control group (e.g. theory-only or measurement-based) for comparison.
- The intuitive nature of the test makes it harder to measure actual learning outcomes objectively.
- Peer interaction and facilitator presence may have subtly influenced observations and interpretations.

D3.1.5 Discussion

The study confirmed that intuitive testing offers valuable learning moments—especially when students are allowed to explore and reflect freely. Hands-on experience helped them move beyond surface-level guesses and into more informed reasoning. Students began to see how certain tests revealed real differences, while others required more interpretation.
The misconception that “heavy equals dense” came up often, but the water displacement test directly challenged that assumption. Meanwhile, the resonance test proved difficult for most, suggesting that some sensory tests may need more scaffolding to be effective.
This balance of trial, feedback, and reflection supports an intuitive learning loop—one that aligns well with early-stage engineering education.

D3.1.6 Conclusions

The IMI user test showed that students can gain meaningful insights about materials through simple, hands-on testing. While intuition alone isn’t always reliable, it becomes much more effective when supported by a variety of sensory-based comparisons.
Positives:

- Scratch and heat transfer tests were clear and informative.
- Density test revealed strong misconceptions and created valuable discussion.
- Confidence and understanding improved by the end of the test.

Negatives:

- Provide brief explanations or demonstrations before each test.
- Clarify how to interpret more abstract tests like resonance.
- Follow up intuitive testing with structured theory to reinforce correct understanding.

Overall, the study highlights the potential of hands-on, low-tech material exploration—especially when paired with guided reflection and a diverse set of tests.

D3.2 IT Questions and Instructions

This user test is part of a master's research project and consists of two main parts. In the first part, participants are asked to reflect on their prior knowledge and expectations about different materials and their properties. In the second part, they will perform a series of hands-on, sensory-based tests to differentiate materials using qualitative cues such as sound, touch, heat, and conductivity.

Throughout the test, you will be asked to reflect on your experience and understanding by answering a series of questions. These responses will help evaluate the educational impact of intuitive, sensory-based methods in learning about material properties and identification.

Questions Before the Test

1. How do you think materials can be identified using simple, non-technical tests?
2. If you could only hold a material, what would you try to feel for?
3. What properties would you use to differentiate a metal from a polymer?
4. Have you ever done any material identification tests before?
5. On a scale from 1–5, how confident are you in your ability to identify unknown materials using intuition?
6. What do you expect to learn from this kind of hands-on testing?

Students perform tests

You will perform five intuitive, qualitative tests using six materials: Aluminium, Copper, Lead, Polypropylene, ABS, Acrylic, and Wood. These materials represent a range of common engineering materials including metals, plastics, and natural materials.

Questions After Hands-On Testing

7. Which test helped you differentiate materials the most? Why?
8. Were any of the results unexpected? Explain.
9. Did you feel more confident in identifying materials after the hands-on tests?
10. How did your initial expectations compare with your findings?
11. If you were designing a product, which material properties would you now consider more carefully?
12. If you had to teach someone how to identify materials without lab tools, which tests would you recommend and why?
13. “Which material felt heavy but wasn’t dense, or vice versa? What does that say about how we judge materials by feel?”

Summary & Reflection

14. Rate your confidence (1–5) in being able to identify a material group (metal, plastic, wood) based on touch and simple tests.

Instructions for tests (for Student)

Test 1: Electrical Conductivity (LED Circuit Test)

- Clean the surface of each material.
- Insert the sample into the LED test circuit.
- Observe whether the LED lights up.
- Which materials do you expect to conduct electricity?
- Which ones did? Were there any surprises?

Test 2: Scratch Test

- Use a steel nail to apply equal pressure to each material.
- Observe the depth and visibility of scratches.
- Rank the materials from softest to hardest.
- Did your results match your assumptions?

Test 3: Sound Resonance Test

- Tap each material gently with a metal spoon.
- Listen and categorize them as "resonant" or "dull."
- Which materials produced the clearest sound?
- What could be causing these differences?

Test 4: Heat Transfer Test

- Touch and compare how warm each material feels.
- Place each sample on a heated plate for 15 seconds.
- Touch and compare how warm each material feels again.
- Which materials warmed up fastest?
- Which do you think are better insulators or conductors?

Test 5: Density test

- Tie a string around the sample so you can hold it without touching it.
- Weigh the object in air using a digital kitchen scale. Write down the weight in grams.
- Place a cup of water on the scale and tare it (the display should read 0 g).
- Hold the object by the string and fully submerge it in the water **without touching the cup or bottom**.
- Read the new value on the scale – this is the weight of the water displaced, and it equals the object's volume in cm^3.
- Now calculate: **Density = Weight in air / Volume from scale**
- Compare the densities. Which materials were heavier for their size?

D3.3 IT Participant Responses

Table D3.3 Part One -Participant Responses

Participant ID	Pre-Q1	Pre-Q2	Pre-Q3	Pre-Q4	Pre-Q5	Pre-Q6	
IMI 1	Door eraan te voelen en te kijken. Bijvoorbeeld als iets koud aanvoelt, denk ik dat het een metaal is. En als iets er een beetje 'plastic-achtig' uitziet, dan is het vast kunststof.	Op hoe zwaar het voelt, of het warm of koud aanvoelt, en hoe hard het is als je erop drukt.	Metaal is meestal kouder en zwaarder, en kunststof voelt wat zachter aan. En metaal klinkt harder als je erop tikt.	Nee, nog nooit. Alleen een beetje in natuurkunde op de middelbare school, maar niet zo praktisch.	2	Ik denk dat ik materialen beter ga herkennen door het te doen, en dat ik dan sneller zie wat wat is.	Kop > P
IMI 2	Uhm, door hoe het aanvoelt. Dus dingen zoals koud of warm, en hoe zwaar iets is denk ik.	Ik zou letten op temperatuur en hoe ruw of glad het oppervlak is. Gewicht ook wel.	Metaal is vaak zwaarder en kouder. Kunststof voelt wat zachter en warmer.	Nee, dit is eigenlijk helemaal nieuw voor mij.	3	Ik hoop dat ik beter ga begrijpen waarom sommige materialen in producten worden gebruikt.	Kop Pol
IMI 3	Gewoon goed kijken en voelen. Je ziet vaak al of iets metaal of plastic is.	Of het koud is en hoe zwaar het voelt.	Gewicht, temperatuur en glans.	Nee.	3	Of mijn inschattingen een beetje kloppen eigenlijk.	Kop > P
IMI 4	Misschien door gewicht en temperatuur? Ik weet niet precies hoe je dat zou moeten testen zonder apparatuur.	Hoe zwaar het voelt, en of het glad of ruw is.	Ik denk dat metaal kouder aanvoelt en misschien zwaarder is.	Nee, nog nooit. Dit is nieuw voor mij.	2	Ik hoop dat ik leer om materialen te herkennen op gevoel.	Kop > P
IMI 5	Uhm... ik denk dat je naar hoe het voelt moet kijken. Misschien ook of het glimt of zo?	Ik zou letten op hoe glad het is, of het warm of koud is, en hoe zwaar het voelt... denk ik.	Kunststof voelt vaak een beetje zachter en warmer. Metaal is kouder, denk ik? Maar soms is dat moeilijk.	Nee, dit is de eerste keer eigenlijk.	2	Ik hoop dat ik beter leer welke materialen wat zijn. Ik haal ze nu nog best vaak door elkaar.	Kop > P
IMI 6	Door naar functionele eigenschappen te kijken, zoals geleidbaarheid of massa per volume.	Temperatuurgeleiding, oppervlaktehardheid, en massa. Je voelt dat meteen.	Metaal is zwaarder, koeler aan de hand, vaak glanzender. Kunststof is lichter en doffer.	Nee, nog niet. Wel in theorie, niet zo praktisch als dit.	5	Dat ik mijn theoretische kennis ook praktisch kan bevestigen.	Kop > P
IMI 7	Ehh gewoon voelen toch? En beetje schudden of erop tikken ofzo...	Als het zwaar is of koud aanvoelt, dan is het vast metaal. Of niet, soms weet je het niet zeker.	Metaal is kouder denk ik. Maar sommige kunststoffen voelen ook best koel. Dus lastig soms.	Nope, eerste keer dit. Wel leuk eigenlijk.	3	Ik denk dat ik beter ga leren voelen wat wat is. Ik hoop dat ik het een beetje kan onthouden.	Kop Pol
IMI 8	Ik denk dat je via eenvoudige testen zoals voelen, tikken of verwarmen al veel kunt inschatten.	De temperatuur, het gewicht, hoe het oppervlak voelt. Ook hoe het reageert als je erop tikt.	Metaal is meestal koeler, zwaarder en klinkt helderder. Kunststof is vaak warmer, lichter en doffer.	Niet eerder met echte materialen. Alleen theorie op school.	4	Een beter gevoel krijgen bij de eigenschappen van materialen die je normaal niet goed kunt inschatten.	Kop > P
IMI 9	Je voelt het gewoon, of kijkt ernaar. Meer weet ik niet.	Zwaar of niet. Glad of ruw. Klaar.	Metaal is kouder en zwaarder. Kunststof niet.	Nee.	2	Geen idee. Misschien dat ik iets leer.	Kop > P

Table D3.3 Part Two -Participant Responses Continued

Test 4 - Notes	Test 5	Test 5 - Notes	Post-Q1	Post-Q2	Post-Q3	Post-Q4
is snel warm. Aluminium ook, iets Lood... traag maar komt wel. Acryl el even. Kunststoffen blijven Hout doet echt niks.	Lood > Koper > Aluminium > Acryl > ABS > Polypropyleen > Hout	Lood is echt ziek zwaar. Koper ook, voelt log. Aluminium is lichter. Acryl verraste me wel, voelt best massief. ABS en polyprop zijn duidelijk lichter. Hout dreef meteen.	De warmte test. Ik had niet verwacht dat je echt kon voelen dat sommige materialen sneller warm worden. Dat hielp echt om metaal te herkennen.	Ja, ik dacht dat lood heel hard zou zijn, maar het kraste juist supermakkelijk. Dat had ik echt niet verwacht.	Ja, veel zekerder. Vooral omdat ik nu weet waar ik op moet letten.	Sommige dingen klopten, zoals koper dat goed geleidt. Maar andere dingen, zoals hoe zacht lood is, waren echt anders dan ik dacht.
is snel heet, voel ik direct. ium bijna net zo. Lood wordt am warm. Kunststoffen blijven oel. Hout wordt ook nauwelijks	Lood > Koper > Aluminium > Acryl > ABS > Polypropyleen > Hout	Lood is echt zwaar voor z'n formaat. Koper ook. Aluminium is veel lichter. Hout blijft gewoon drijven, logisch.	De kras-test vond ik wel duidelijk. Je ziet meteen verschil in hardheid.	Ja, dat lood zo zacht is. Had juist gedacht dat dat harder zou zijn dan koper.	Ja, het helpt echt om het zelf te voelen en niet alleen op papier te zien.	Sommige dingen kwamen overeen, zoals warmtegeleiding van koper. Maar dingen als resonantie waren moeilijker in te schatten.
snel heet. Alu ook. De rest blijft koud.	Lood > Koper > Aluminium > Acryl > ABS > Polypropyleen > Hout	Lood mega zwaar. Hout dreef. De rest daartussen.	Warmte. Dat voel je echt goed.	Lood was zachter dan ik dacht.	Ja, wel iets.	Best oké, meeste dingen kwamen wel overeen.
werd echt snel warm. Aluminium ood duurde langer. Kunststoffen koel. Hout voelde helemaal niet	Lood > Koper > Aluminium > Acryl > ABS > Polypropyleen > Hout	Lood was echt zwaar voor z'n formaat. Hout dreef. Koper ook zwaar. Acryl voelde zwaarder dan het was.	De kras-test en geleidbaarheid waren het meest duidelijk voor mij.	Ja, vooral dat lood zo zacht was. Had ik niet verwacht van metaal.	Ja, ik snap het nu beter dan eerst.	Sommige verwachtingen waren fout. Vooral over lood.
werd echt snel warm. Alu ook. leed langer. De rest voelde bijna rm aan.	Lood > Koper > Aluminium > Acryl > ABS > Polypropyleen > Hout	Lood is heel zwaar. Koper ook wel. Hout dreef. Kunststoffen zijn licht. Acryl voelt zwaarder dan verwacht.	De warmte-test, daar voelde ik het duidelijkst verschil.	Ja, dat lood zo zacht was! Ik dacht altijd dat metaal hard moest zijn.	Ja, ik voel me nu wel zekerder dan aan het begin.	Ik zat er vaak naast. Vooral bij lood had ik het mis.
en aluminium geleiden snel . Lood traag. Kunststoffen zijn ren. Hout praktisch inert.	Lood > Koper > Aluminium > Acryl > ABS > Polypropyleen > Hout	Lood heeft duidelijk hoogste dichtheid. Hout het laagst. Kunststoffen variëren maar zijn allemaal relatief licht.	De dichtheidstest gaf mij de meeste informatie. Objectief en makkelijk te interpreteren.	Dat lood zo zacht is verbaasde me. Had het harder verwacht.	Zeer zeker, bevestigde mijn verwachtingen grotendeels.	Alles kwam redelijk overeen met mijn voorspellingen, behalve hardheid van lood.
meteen warm, aluminium snel ood komt daarna. Kunststoffen koud. Hout voel ik niks.	Lood > Koper > Aluminium > Acryl > ABS > Polypropyleen > Hout	Lood superzwaar. Hout dreef gewoon. Kunststoffen licht, logisch. Koper en alu ergens ertussenin.	Dichtheidstest vond ik het duidelijkst, je ziet en voelt het tegelijk.	Lood is echt mega zacht... wist ik niet. Dacht dat metaal altijd hard was.	Ja best wel, vooral door zelf te doen.	Ik had een paar keer ongelijk haha. Vooral over lood dus.
was direct warm. Aluminium snel. Lood minder snel. toffen bleven koel. Hout lijks verschil.	Lood > Koper > Aluminium > Acryl > ABS > Polypropyleen > Hout	Lood was zwaar ondanks klein volume. Hout dreef. Kunststoffen waren zoals verwacht lichter dan metalen.	De hardheidstest. Je ziet duidelijk verschil en het is makkelijk uit te voeren.	Ik had niet verwacht dat lood zo zacht zou zijn. Dat viel op.	Ja, het zelf doen maakt het inzichtelijker dan alleen lezen.	Bijna alles kwam overeen met wat ik had verwacht, op de hardheid van lood na.
is warm. Kunststof niet. Simpel.	Lood > Koper > Aluminium > Acryl > ABS > Polypropyleen > Hout	Lood zwaar. Hout licht. De rest daartussenin.	Weet niet. Misschien die met gewicht.	Lood was zacht. Dat had ik niet gedacht.	Beetje.	Sommige dingen klopten. Andere niet.

Test 1	Test 1 - Notes	Test 2	Test 2 - Notes	Test 3	Test 3 - Notes	Test 4
per > Aluminium > Lood > Acryl > ABS olypropyleen > Hout	Oké koper doet het. Aluminium ook... iets minder fel? Lood... huh, zou toch moeten... niks. Acryl niks. Ja nee hout zeker niet.	Acryl > Aluminium > Koper > ABS > Polypropyleen > Lood > Hout	Acryl... gaat moeizaam, bijna niks te zien. Aluminium krast wel, maar niet diep. Koper... iets makkelijker. ABS geeft al wat sneller mee. Polypro is echt zacht, spijker glijdt er bijna in. Lood meteen een	Koper > Aluminium > Acryl > ABS > Polypropyleen > Lood > Hout	Koper klinkt mooi, echt zo'n ping. Aluminium ook wel. Acryl klinkt een beetje hol. ABS is dof. Polypro ook. Lood... beetje een doffe plof. Hout klinkt nergens naar.	Koper > Aluminium > Lood > > Polypropyleen > Hout
per > Aluminium > Lood > Acryl > ypropyleen > ABS > Hout	Koper doet 't meteen, fel licht. Aluminium ook, iets zwakker. Lood... niks? Apart. Acryl en die plastics doen sowieso niks denk ik.	Aluminium > Acryl > Koper > ABS > Polypropyleen > Hout > Lood	Alu is best hard, moeilijk te krassen. Acryl komt ook niet ver. Koper zit ertussenin. Kunststoffen krassen makkelijk. Lood? Echt zacht, bijna alsof je erin duwt.	Aluminium > Koper > Acryl > ABS > Lood > Polypropyleen > Hout	Aluminium klinkt echt fel. Koper ook, maar iets minder scherp. Acryl best oké. De rest klinkt gewoon dof of nauwelijks iets.	Koper > Aluminium > Lood > > ABS > Polypropyleen
per > Aluminium > Lood > Acryl > ABS olypropyleen > Hout	Koper aan. Aluminium ook. Lood... nee. Kunststof niks. Hout natuurlijk niet.	Aluminium > Acryl > Koper > ABS > Polypropyleen > Hout > Lood	Alu krast lastig. Acryl ook. Lood superzacht. Rest valt ertussenin.	Koper > Aluminium > Acryl > ABS > Polypropyleen > Lood > Hout	Koper klinkt lang. Alu iets minder. Kunststof klinkt dof.	Koper > Aluminium > Lood > > ABS > Polypropyleen
per > Aluminium > Lood > Acryl > ABS olypropyleen > Hout	Koper werkte meteen. Aluminium ook. Bij lood gebeurde niks, dacht dat die ook zou geleiden. Kunststof en hout deden niks zoals verwacht.	Acryl > Aluminium > Koper > ABS > Hout > Polypropyleen > Lood	Acryl kon ik bijna niet krassen. Aluminium ook lastig. Lood... wow, dat is echt zacht. Kunststoffen ertussenin.	Koper > Aluminium > Acryl > Lood > ABS > Polypropyleen > Hout	Koper klinkt helder. Aluminium ook. Acryl iets holler. Lood was dof, klonk gek. Kunststof en hout klonken allebei niet echt.	Koper > Aluminium > Lood > > Polypropyleen > Hout
per > Aluminium > Lood > Acryl > ABS olypropyleen > Hout	Oké... koper doet het meteen. Aluminium ook, iets zwakker. Lood... hmm, dacht dat die ook zou werken. Kunststof... niks. Hout ook niet.	Aluminium > Acryl > Koper > ABS > Polypropyleen > Lood > Hout	Alu krast bijna niet. Acryl ook niet echt. Koper krast wel een beetje. Lood... wow, dat gaat supermakkelijk. Kunststof ertussen.	Aluminium > Koper > Acryl > ABS > Lood > Polypropyleen > Hout	Alu klinkt heel helder. Koper ook. Acryl is een beetje dof. Kunststof en hout... tja, moeilijk te horen.	Koper > Aluminium > Lood > > Polypropyleen > Hout
per > Aluminium > Lood > Acryl > ABS olypropyleen > Hout	Koper en aluminium geven duidelijke geleidbaarheid. Lood verrassend minder, waarschijnlijk door oxidatie of legering. Kunststoffen en hout isoleren zoals verwacht.	Acryl > Aluminium > Koper > ABS > Polypropyleen > Hout > Lood	Acryl is hard, spijker maakt nauwelijks krassen. Aluminium veert iets mee. Lood direct diepe groef, dus zacht. Kunststoffen ertussenin.	Koper > Aluminium > Acryl > ABS > Polypropyleen > Lood > Hout	Koper geeft lang resonantiegeluid. Aluminium net iets korter. Acryl klinkt hol. Kunststoffen dof. Lood dempt alles.	Koper > Aluminium > Lood > > Polypropyleen > Hout
per > Aluminium > Lood > Acryl > ypropyleen > ABS > Hout	Oké LED doet het bij koper, ja logisch. Aluminium ook. Lood... huh niks? Had ik niet verwacht. Kunststoffen niks. Hout natuurlijk ook niks.	Acryl > Aluminium > Koper > ABS > Polypropyleen > Hout > Lood	Acryl krast bijna niet. Aluminium ook niet echt. Koper ietsje. Lood... wow je gaat er zo doorheen. Kunststof krast makkelijker dan ik dacht.	Aluminium > Koper > Acryl > ABS > Lood > Polypropyleen > Hout	Alu pingt! Koper ook. Acryl... iets. De rest is echt doodgeluid. Lood klinkt als... niks.	Koper > Aluminium > Lood > Polypropyleen > ABS > Hou
per > Aluminium > Lood > Acryl > ABS olypropyleen > Hout	Koper en aluminium geleiden goed. Lood niet zoals ik had verwacht. Kunststoffen en hout deden niets, zoals verwacht.	Acryl > Aluminium > Koper > ABS > Polypropyleen > Hout > Lood	Acryl liet bijna geen kras zien. Aluminium en koper iets meer. Lood was opvallend zacht. Kunststoffen waren gemiddeld.	Koper > Aluminium > Acryl > ABS > Polypropyleen > Lood > Hout	Koper gaf het langste geluid, aluminium iets korter. Acryl klonk redelijk hol. Kunststoffen klonken dof. Lood nauwelijks hoorbaar.	Koper > Aluminium > Lood > > Polypropyleen > Hout
per > Aluminium > Lood > Acryl > ABS olypropyleen > Hout	Koper en alu werkten. Lood deed niks. Kunststof ook niet. Logisch.	Acryl > Aluminium > Koper > ABS > Polypropyleen > Lood > Hout	Spijker krast makkelijk in lood en hout. Acryl bijna niet. De rest ertussen.	Koper > Aluminium > Acryl > ABS > Polypropyleen > Lood > Hout	Klinkt of het pingt of niet. Koper pingt. Hout niet.	Koper > Aluminium > Lood > > Polypropyleen > Hout

Post-Q5	Post-Q6	Post-Q7	Reflectie-Q1	Reflectie-Q2	Reflectie-Q3	Reflectie-Q4
Dichtheid en warmtegeleiding, denk ik. En ook hoe iets aanvoelt bij aanraking.	De tik-test en de warmte test. Omdat die snel iets laten zien zonder dat je iets kapotmaakt.	Acryl voelde zwaar maar was niet zo dicht als ik dacht. Gewicht is dus best misleidend soms.	4	Dat dingen echt anders kunnen voelen dan je verwacht. Vooral bij dichtheid en hardheid.	Misschien een overzichtstabel met wat normaal is voor elk materiaal, als check achteraf.	Ze helpen veel, vooral bij geleidbaarheic en hardheid. Maar soms denk je dat iets zwaar is en dus 'stevig', terwijl dat niet zc is.
Hardheid en of het snel warm wordt. En hoe het klinkt bij aanraken zelfs.	Ik zou de tik-test gebruiken en de kras-test. Omdat je dan direct verschil voelt en hoort.	Acryl leek zwaarder dan het eigenlijk was qua dichtheid. Je kunt je dus makkelijk vergissen.	4	Dat materialen echt verschillend aanvoelen in de hand en dat dat iets zegt over hun eigenschappen.	Misschien iets meer uitleg vooraf bij elke test.	Ze zijn handig, maar dingen zoals gewicht of klank kunnen je wel foppen als je te snel oordeelt.
Hoe stevig het is en of het warm wordt.	Kijken, voelen, tikken. Simpel maar werkt.	Acryl leek zwaarder dan het is. Gewicht zegt niet alles.	4	Dat dingen anders voelen dan je denkt. Vooral bij warmte.	Misschien een beetje meer uitleg bij wat de volgorde zou moeten zijn.	Gewicht misleidt. En resonantie vond ik lastig te beoordelen.
Ik zou meer letten op hoe stevig iets is en of het warmte goed doorgeeft.	De kras-test, en de tik-test. Die geven snel verschil.	Acryl voelde zwaar maar had toch een lagere dichtheid dan verwacht.	4	Dat wat ik voelde vaak wel klopte, maar soms misleidend was zoals bij lood.	Misschien een soort voorbeeld vooraf van elk materiaal.	Zintuigen helpen veel, maar gevoel over gewicht klopt niet altijd met dichtheid.
Hardheid en dichtheid zou ik beter overwegen nu.	Ik zou aanraden om te tikken en krassen, en voelen of het koud is.	Acryl voelde zwaar, maar verplaatste toch veel water. Dus niet zo dicht als ik dacht.	3	Ik heb echt geleerd dat dingen anders kunnen zijn dan je denkt. Vooral hoe ze aanvoelen.	Misschien een soort voorbeeld vooraf van hoe elk materiaal klinkt of voelt.	Ja, gewicht is echt misleidend. En resonantie vond ik moeilijk om goed te beoordelen.
Voor ontwerp: geleidbaarheid, thermische respons, en massa.	Dichtheid via verplaatsen, resonantiegeluid, en geleiding met simpele schakeling.	Acryl voelde massief, maar bleek niet extreem dicht. Gewicht zonder context is misleidend.	5	Zintuigen geven directe feedback die theorie tot leven brengt.	Geen aanpassingen nodig. De setup is logisch en leerzaam.	Warmte en resonantie kunnen lastig zijn om zuiver te beoordelen op gevoel.
Ik zou goed kijken naar gewicht, hardheid en of het warm wordt.	Tik-test en gewoon in je hand houden. Zegt al veel.	Acryl was zwaar, maar niet super dicht. Dus gevoel klopt niet altijd.	3	Door te voelen merk je dingen die je niet uit een plaatje haalt.	Misschien iets meer uitleg bij wat je moet voelen of horen.	Soms denk je dat zwaar gelijk staat aan dicht, maar dat klopt dus niet altijd.
Voor een product zou ik goed letten op gewicht en thermisch gedrag, afhankelijk van de toepassing.	Warmtegeleiding, resonantie en een kras-test zijn makkelijk uit te voeren en geven veel informatie.	Acryl voelde relatief zwaar maar bleek minder dicht. Dus gevoel en werkelijkheid komen niet altijd overeen.	4	Dat tast echt iets toevoegt aan het begrijpen van eigenschappen zoals dichtheid en geleidbaarheid.	Eventueel een checklist per test om te weten waar je op moet letten.	Het gevoel van massa kan je misleiden als je niet ook naar volume kijkt.
Licht of zwaar, hard of zacht.	Gewoon voelen. Meer hoeft niet.	Je zit er soms naast als je alleen op gevoel afgaat.	2	Je moet dingen doen om het echt te begrijpen.	Minder uitleg, sneller beginnen.	Gevoel kan misleiden. Bijvoorbeeld bij gewicht.

D3.4 - IT Consent Form

TU Delft – Informed Consent Form

Title of Research Project: *Understanding Material Properties in Engineering Education*

Researcher: Wouter Huisman, MSc Integrated Product Design, TU Delft

Participant Information

You are invited to take part in a research study that explores how students learn about material properties using hands-on and analytical testing methods. The study includes activities such as performing a 3-point bending test using a 3D-printed device and several intuitive material identification tests using touch, sound, temperature, and weight. You will also be asked to answer a few short questions before and after the tests to reflect on your understanding and experience.

Your participation is voluntary. You can withdraw from the study at any time without giving a reason. The study will take approximately 45–60 minutes.

No personally identifiable information (such as your name or contact details) will be collected. Data from your responses and test results will be stored securely, anonymised, and may be used for academic publications, presentations, and teaching materials. Only the research team will have access to the full data. Data will be stored for up to 10 years, according to TU Delft research data guidelines.

The tests are not CE-certified. There are minimal risks involved. The equipment used is safe, manually operated, and has been pre-tested. Instructions will be provided, and the researcher will supervise all activities.

If you have questions about the study, please contact: Wouter Huisman,

Consent

Please tick the boxes to confirm:

☐ I have read and understood the information above.

☐ I voluntarily agree to participate in this study.

☐ I understand I can withdraw at any time without explanation.

☐ I agree that anonymised data from this study may be used for academic publication, education, or further research.

☐ I give permission for my anonymised data to be archived for future research and teaching purposes.

Name of Participant: ______________________

Signature: ____________________

Date: _______________________

Researcher Declaration:

I, the undersigned, confirm that I have provided a clear explanation of the study and answered any questions to the best of my ability.

Researcher Name: ______________________

Signature: ____________________

Date: _______________________

Appendix E - Structured Track (ST)

E1 - Considerations

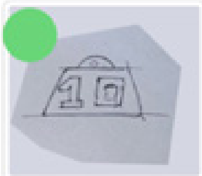
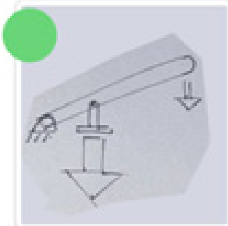
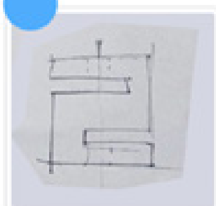
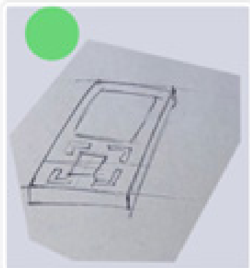
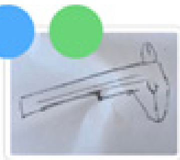
E1.1 - Methods

Table E1.1 Methods

Method / Concept	Reason Considered	Why Rejected / Accepted
Tensile testing (weights or pulleys)	Direct way to measure strength, widely used in engineering	Too high force required. unsafe and impractical for classrooms
Vickers / Brinell indentation test	Common structured hardness tests used in industry	Needs high precision and lighting. hard to use unsupervised
Fracture toughness (Charpy or drop weight)	Teaches failure modes and energy absorption	Destructive and unsafe. not suitable for education context
Durometer (polymer hardness)	Simple for polymers; uses readily available tools	Too narrow in application. doesn't cover enough materials
Scratch tests with measurement	Could give structured comparison across materials	Inconsistent and hard to scale. overlaps with intuitive tests
3-point bending (included)	Safe and compact method to measure stiffness	Selected: measurable, safe, and easy to build

E2 - Morphological Chart

Table E2. Morphological Chart

Concept 1 / Concept 2 / Concept 3			
Force Input	 Manual force	 Weights	
Force Translation	 Threaded	 Springloaded	 Levered
Force Measurement	 Mechanical Indicator	 Load Cell	 Scale
Deflection Measurement	 Built in Analogue	 External Analogue	

E3 - Evaluation Matrix

Table E3. Evaluation Matrix

Concept	1. Engagement	2. Scientific Precision	3. Real-World Relevance
Concept 1	Moderate – students actively turn the screw, but it's slower and less tactile than others.	High – load cell gives actual force values, supports structured analysis.	High – reflects common lab methods and professional testing setups.
Concept 2	High – immediate feedback, tactile pressing action is satisfying and quick.	Moderate – spring deflection gives visual cue, but not calibrated.	Moderate – conceptual link to applied force exists but less formal.
Concept 3	High – very hands-on and physical, simple to understand.	Low – uses fixed weights but no measurement of force or deflection.	High – visual, weight-based tests mirror how loads act in products.

4. Reproducibility	5. Practicality	6. Safety
High – repeatable setup with fixed screw and digital reading.	Moderate – needs electronics, careful build, and basic calibration.	High – fully enclosed force path and low-risk components.
Moderate – depends on spring quality and user force consistency.	High – simple mechanical parts, no wiring, and quick resets.	High – low-force, fully mechanical and intuitive to use.
Low – position-based weight placement and human error reduce consistency.	Low – bulky, fiddly, and not ideal for quick classroom use.	Moderate – some risk from dropped weights or unstable placement.

E4 - Prototyping

E4.1 -Prototyping Sketches

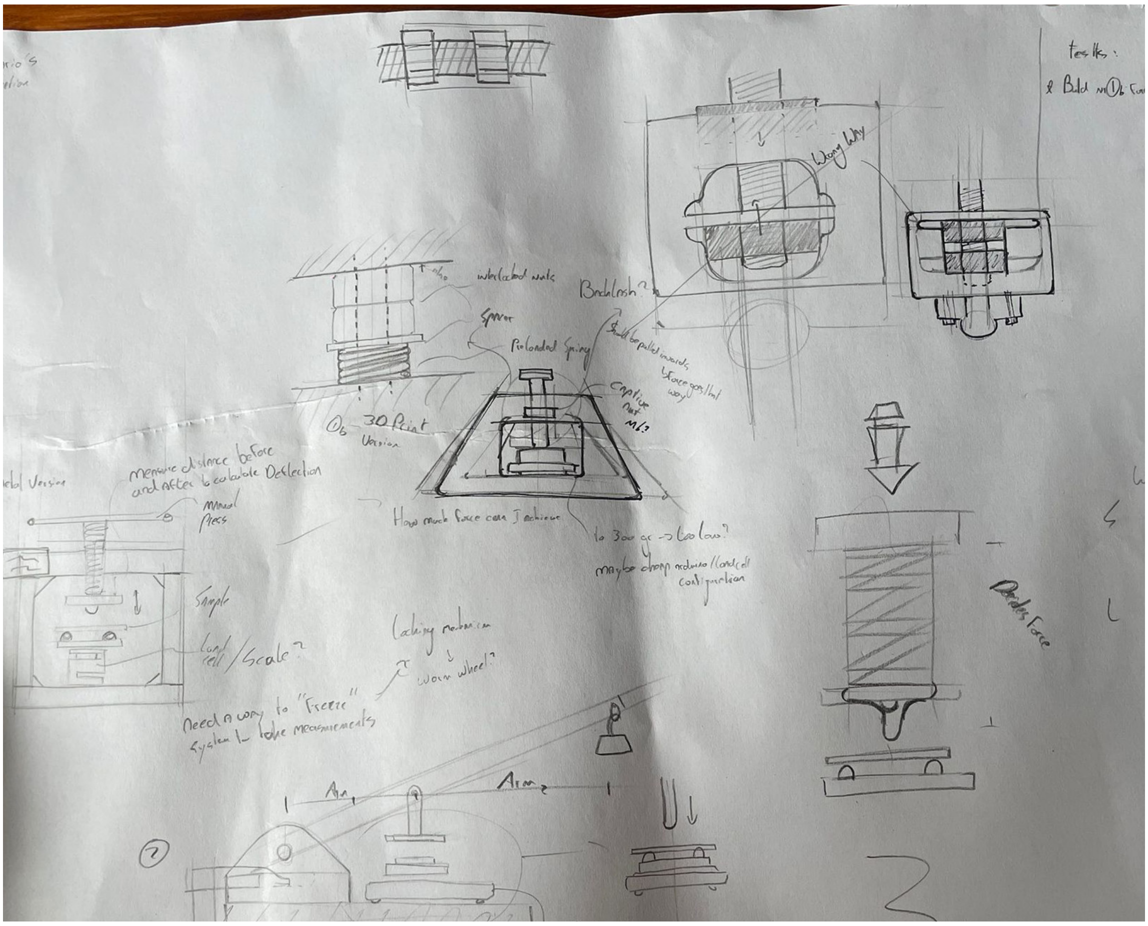


Figure E4. Some Prototypin Sketches

E4.2 Prototyping Details

Prototype 1 – Proof of Principle

This first version was built to test the most basic function: whether an M8 bolt could apply enough force to visibly bend a material strip in a controlled way. The prototype was 3D-printed in two parts, with a captive nut sandwiched between them. This let the bolt rotate cleanly while staying aligned.

Why M8?
M8 was chosen because it strikes a good balance: the thread pitch is coarse enough to move relatively fast, but fine enough to allow controlled input. It's also a standard size, easy to turn by hand, and compatible with cheap hardware. There was no need for ultra-precise micro-adjustments at this stage.
The material strip used in testing was aluminium, which showed visible bending under load without permanent deformation. This confirmed that the basic concept worked.

Prototype 2a – First Integrated Version

This version was the first step toward a more complete setup. The bolt was now fixed in the housing using a nut and washer system, and a second nut was embedded in a 3D-printed indenter part. As the bolt rotated, the nut (and therefore the indenter) moved up or down.
The indenter was blocked from rotating by being sandwiched between the housing walls, it could only move vertically. The support structure below the strip was also 3D printed and included two flat "anvils" for the material strip to rest on. These anvils matched the spacing needed for a simplified three-point bending setup.
Small cantilever tabs were added to both the indenter and support, so that a calliper could be used to measure the deflection. These notches were positioned to give a clean line of contact without interfering with the strip.
A precision scale (Max 200g) was placed under the support to get an early idea of the applied force. This couldn't measure enough force for a lot of materials but is was really accurate. The bolt was rotated with a wrench.

Prototype 2b – Functional Refinement

Several issues from 2a were addressed here. First, a 3D-printed knob was added so the bolt could be rotated by hand. This made the interaction feel more deliberate and intuitive, important for use in a classroom setting.
One problem was backlash: there was some play in the bolt before the indenter started moving. To fix this, the indenter was redesigned to hold two nuts slightly apart, allowing the part to flex and preload the thread. This added tension removed the gap and made movement smoother, especially near the starting point.
The calliper system was also changed. A new part was added to the front of the housing, creating a slot for a standard calliper. The measuring pin could now be pushed down directly onto the cantilever tab of the indenter, making the measurement easier to control and more repeatable.

Prototype 2c – Measurement Stability

The kitchen scale was replaced with a 5kg button load cell, allowing for actual measurement of the applied force. The support part was bolted directly onto the load cell, giving a more consistent reading than just placing it on a scale.
In testing, it became clear that the anvil could flex slightly when under load. Even though this movement was small, it was enough to affect the deflection reading.
The system adjusted so the bottom of the calliper now rests on the indenter tab, and the measuring bar moves down until it hits the support part. Now the deflection is measured between the indenter and the support part, eliminating measurement errors because of housing flex.
The housing itself stayed mostly the same, but the indenter and support were both modified to include small contact points for the calliper pin and measuring surface. This change improved accuracy and reliability without adding much complexity.

E5 - Mechanical Evaluation

E5.1 - Deflection Readings

A static load was applied to the button load cell to observe measurement stability over time. Two recorded graphs show a gradual decrease in the measured weight, despite no change in the applied load. This drift indicates potential limitations in long-duration readings and highlights the need for recalibration or quick-read protocols in educational use.

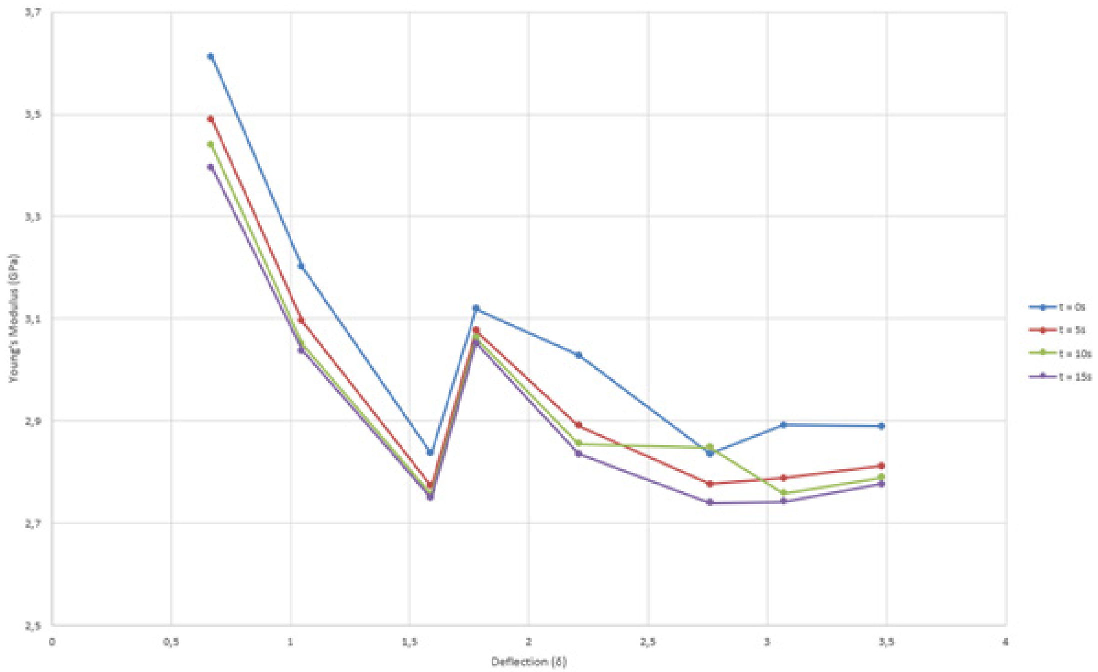


Figure E5.1.1 Young's modulus over Time

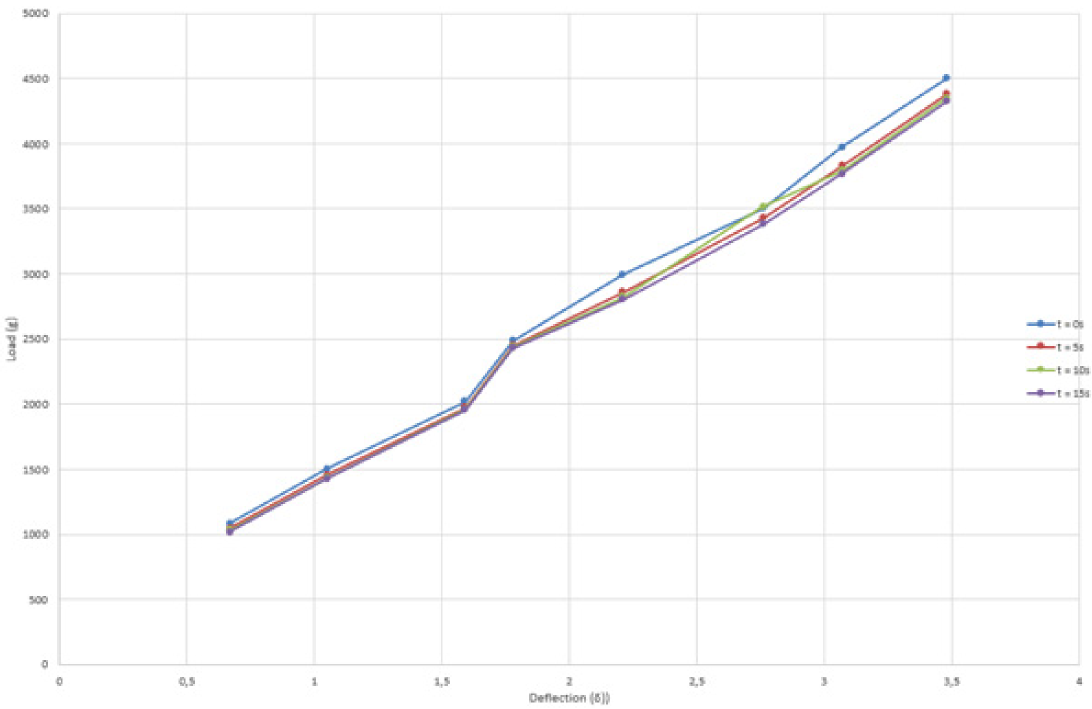


Figure E5.1.2 Load over Time

E5.2 Off Axis loading of load cell

To assess the sensitivity of a button load cell to off-axis loading, a 2567 g weight was placed directly on the centre point and then moved in 1 mm increments. At 10 mm offset, the recorded weight increased to 2688 g. The result shows measurable deviation with off-centre loading, underlining the need for consistent axial placement during testing.

Figure E5.2.1 Load cell test a

Figure E5.2.2 Load cell test b

E6 - Iteration Changes

Following user testing and the mechanical evaluation, the structured track was fully redesigned to improve accuracy, usability, and buildability. This iteration represents a shift from early-stage prototyping to a classroom-ready setup, built around clearer feedback, tighter mechanical tolerances, and simplified assembly.

The changes were based on observed problems in the initial prototype (Chapter 8) and checked against the six Main Drivers. While the final version has not yet been validated mechanically or through user testing, each update is grounded in practical needs and designed for scalable use in education. Full validation will take place after the Greenlight phase.

Laser-Cut Housing

The original 3D-printed housing was replaced with a laser-cut plywood construction using 5 mm triplex. This change was made to improve production speed, reduce warping, and simplify alignment. Laser cutting also allows engraved instructions to be added directly to the side panels, improving usability during independent classroom use (see Figure E.x).

Bar-Type Load Cell (10 kg)

The previous 5 kg button load cell was replaced with a 10 kg bar load cell, which is easier to source and provides a stiffer, more stable input under load. It reduces the risk of tilting under contact from the callipers and is expected to provide more consistent readings. This change aims to remove reliance on a single manufacturer, supporting long-term reproducibility, by hardware documentation and engineering sources (Morehouse Instrument Company, 2021; Interface Force Measurement Solutions, 2024; SparkFun Electronics, n.d.).

Dual-Bearing Bolt Mount

The M8 loading bolt is now mounted using two standard 608zz bearings, tensioned against each other to prevent lateral play. This setup is expected to allow smoother force input with less friction or wobble (see Figure E.x). The bearings are widely available and robust, contributing to overall feasibility and maintenance simplicity.

Set Screw Alignment for Indenter

The preload on the indenter was reduced to lower friction during low-force measurements. To maintain precise vertical alignment, six countersunk set screws were added to the housing (three per side). These contact small guide surfaces and constrain the indenter's movement to a single vertical axis (see Figure E.x). This solution is intended to improve measurement accuracy while keeping the system low-tech and serviceable.

Redesigned Knob with Vernier Scale

The rotation knob was redesigned to avoid interference with the callipers and now includes a 25-division vernier scale. Each step corresponds to ~0.05 mm of travel — matching the resolution of the callipers. This feature is intended to give students a physical reference point for applied force and help cross-check manual input against digital readings (see Figure E.x).
It also reinforces the use of the setup as real mechanical testing equipment, supporting structured engineering reasoning and visual interpretation.

Electronics Update: Compact Controller and Amplifier

The electronics system was redesigned around a compact Seeed Studio Xiao microcontroller (final model Name), paired with an HX711 load cell amplifier and a small OLED screen. These components now fit inside a dedicated electronics compartment in the housing, keeping them protected and tamper-resistant during use.

Geometry Standardisation

As part of this iteration, the geometry of the test setup and sample was also standardised. These changes support repeatable testing across different materials, better alignment with educational standards, and improved mechanical reliability under load.

Span Length – 40 mm

The span length was reduced from 50 mm to 40 mm. This allows larger, more visible deflections under modest forces, keeping loads within the range of the 10 kg load cell and enhancing clarity in classroom settings. It also reflects allowances in ISO 178:2019 for reduced span lengths when sample size or stiffness constraints apply.

Support & Indenter Diameter – 5 mm

The diameter of both the supports and indenter was set to 5 mm, offering a more standardised contact area that reduces stress concentrations and damage risk — especially in brittle or thin materials. Matching diameters also simplify production and maintenance.

Standard Sample Size – 60 × 15 × 1.5 mm

A standard sample size was defined for all structured tests:
60 mm length, 15 mm width, 1.5 mm thickness.
This size supports compatibility with the 40 mm span and provides adequate bending behaviour across a wide range of classroom-safe materials. It also simplifies sourcing and reduces material use per test.

Appendix F - Structured Track User Test

F1 - Full Study

F1.1 Introduction

This study explores how students understand material stiffness, specifically Young's modulus, when they learn through both theory and hands-on experimentation. The concept is a staple in materials science, but for many first-year students, it's abstract and difficult to relate to. By combining calculation with a physical 3-point bending test, the goal was to find out: does doing the test help students understand what the numbers really mean?

F1.2 Methods

Eight students from TU Delft took part in a structured user test with two parts. First, they completed a theoretical exercise calculating Young's modulus using a standard formula and given values. Then, they performed the same test physically using a 3D printed bending device. Before, during, and after the test, participants answered open questions about their expectations, understanding, and experience.
Their responses were analysed to assess how well they grasped the concept, how confident they felt, and what they found useful or confusing. All questions, answers and the consent form can be found in appendices F2 through F4.

F1.3 Results

Most students began the test with a vague idea of what Young's modulus was—usually something about "stiffness" or "how much something bends." The theory part felt abstract to them, especially when units didn't line up or when converting measurements. Once they started the hands-on part, things changed.

Key insights:
- Students reported stronger understanding after the physical test. Several described "aha" moments.
- Most realized bending is not the same as hardness—a common initial misconception.
- Confidence scores were generally higher after the test (mostly 4–5 out of 5).
- Nearly all preferred doing the physical test first to better grasp the theory afterward.
- The importance of measurement precision became clear through real trial and error.
- Feeling, doing, and seeing made the modulus more concrete.

Student observations:
- "Now I get what that number means."
- "You really have to think about where and how you measure."
- "It was fun and helpful, but tricky to do perfectly."

F1.4 Strengths and Limitations

Strengths:
- Mixed-method design gave students a chance to compare theory and practice directly.
- Open-ended questions encouraged honest, detailed reflections.
- Participants were representative of early-stage engineering students—little prior exposure to materials testing.

Limitations:
- Small sample size (n=8) means the findings are more illustrative than conclusive.
- No comparison group (e.g., theory-only) limits the ability to isolate impact.
- Self-reported understanding and confidence aren't the same as measured knowledge gains.
- Facilitator presence may have influenced how openly students critiqued parts of the process.

F1.5 Discussion

This small study reinforces something intuitive: abstract concepts become easier to grasp when you interact with them physically. For most students, theory alone didn't "click." But the hands-on test brought the idea to life. That's where the shift happened—from seeing Young's modulus as a number to understanding it as a physical behaviour.

Still, learning wasn't flawless. Measurement was confusing. Some students weren't sure when to record force. These bumps were part of the learning, but they also highlight where the test design can improve.

F1.6 Conclusions

The combination of calculation and physical testing helped students build a clearer, more intuitive understanding of Young's modulus. Doing the test gave meaning to the formula—and made the learning stick.

Positives:

- Physical testing improved conceptual clarity.
- Confidence increased for most students.
- Misconceptions (like "bending = hardness") were corrected.

Negatives:

- Give clearer visual instructions or checklists.
- Mark measurement points more precisely.
- Consider introducing the physical test before the theory to support early comprehension.

This approach is promising, especially for beginners. With some tweaks, it could become a powerful tool in introductory materials education.

F2 - ST Questions and Instructions

3-Point Bend Test User Experience

This user test is part of a master's research project and consists of two main parts. In the first part, participants are asked to complete a **theoretical calculation** of a 3-point bending test using provided values. In the second part, they will **conduct the test physically** using a 3D printed device designed to measure force and deflection.

Throughout the test, you will be asked to reflect on their experience and understanding by answering a series of questions. These responses will help evaluate the educational impact of combining theoretical and hands-on approaches to learning about material properties.

Questions before the Test

1. What do you think Young's modulus tells us about a material?
2. How is Young's modulus usually determined?
3. Have you ever seen or done a material test before?
4. On a scale from 1–5, how confident are you in your ability to measure material stiffness?
5. What do you expect to learn from doing the physical version of this test?

Student performs part one

Questions after part one

1. What do you think is happening in the material when you apply force?
2. Do you feel like you understand what deflection represents in this context?
3. How confident are you in your calculated Young's modulus? Why?
4. Was any part of the formula or calculation confusing or abstract?
5. If someone asked you to explain the theory behind a 3-point bending test, how would you start

Student performs part two

Questions after Part Two

After completing the test, answer the following:

1. What did you learn from the physical test that you didn't get from the theoretical calculation?
2. Was anything surprising about how the material behaved?
3. Did you have any misconceptions that were corrected during the hands-on part?
4. On a scale from 1-5, how confident are you now in explaining what Young's modulus means?
5. Would you start with theory or the physical test if you had to teach someone else? Why?
6. Any final thoughts or feedback about the learning experience or the device?

Part Two: Hands-On Testing (page for student)

Instructions:

You will now perform a physical 3-point bend test using a custom 3D printed device:

1. Insert the beam into the tester, resting it on the two support anvils.
2. Turn the knob slowly to lower the central loading nose until it contacts the beam.
3. Insert calipers through the side slots to measure the initial height (before force is applied).
4. Continue lowering the loading nose incrementally, noting the force (from the load cell) and corresponding deflection (change in height).
5. Record 3–5 pairs of force and deflection measurements.
6. Measure the beam's width, height, and span length.
7. Calculate Young's modulus for each pair, then average your values.

Be consistent with your units and speak out loud as you work through the steps.

F3 - ST Participant Responses

Table F3. Part One - Participant Responses

Participant ID	Pre_Q1: What is Young's modulus?	Pre_Q2: How is it determined?	Pre_Q3: Prior experience with material tests?	Pre_Q4: Confidence (1–5)	Pre_Q5: Expectations for physical test	Theory_Q1: What happ to material under for
3PBT 1	Volgens mij zegt het iets over hoe stijf of buigzaam een materiaal is. Dus hoe makkelijk het buigt als je er kracht op zet. Een hoge modulus betekent dat het materiaal moeilijk buigt.	ik denk door een kracht op het materiaal te zetten en dan te meten hoeveel het doorbuigt. En dan gebruik je daar een formule voor. Iets met kracht, lengte en buiging.	Een beetje, op de middelbare school wat dingen en op de uni heb ik ook wel naar dingen gekeken, maar dat waren meer demonstraties dan dat ik het zelf echt deed, of dat een groepsgenootje er mee bezig was en ik alleen keek.	Een 3. Ik snap in theorie hoe het moet, maar ik heb het nog nooit gedaan.	Dat weet ik niet zo goed eigenlijk. Vast kleine dingen die ik niet verwacht had	Dan wordt het materiaal een beetje ingec uitgerekt, afhankelijk van hoe je de krach dit geval buigt het gewoon door omdat je bovenaf op drukt.
3PBT 2	ik denk dat het iets zegt over hoe flexibel een materiaal is. Dus hoeveel het kan buigen voordat het breekt of terugveert.	Ik heb geen flauw idee eigenlijk, ik denk iets met krachten meten?	Ik heb hier op de uni wel dingen gezien maar het nog nooit zelf gedaan.	een 2 denk ik. Ik weet echt niet zo goed hoe dat moet en ik ben niet zo handig met meetapparaten.	1. Vooral hoe het er in het echt uitziet en hoe je het moet doen. En ik hoop dat ik dan de theorie beter snap doordat ik het zie gebeuren.	Dan buigt het een beetje door in het mid hoe meer kracht, hoe meer het buigt.
3PBT 3	hoeveel kilo je op iets kan zetten?	Gewoon kracht meten, denk ik?	Nee nooit gedaan.	2 Geen idee of ik het goed doe.	Ik hoop dat het iets duidelijker wordt.	Het zakt een beetje in, soort van.
3PBT 4	Het geeft aan hoeveel spanning er nodig is om een bepaalde vervorming in een materiaal te veroorzaken. Hoe hoger de waarde, hoe stijver het materiaal is.	Je zet een kracht op het materiaal, meet hoeveel het vervormt en gebruikt dan de formule om het uit te rekenen.	Ja we hebben een keer zo'n trekproef gedaan.	4. Ik heb er vertrouwen in, vooral in de theorie.	Ik denk dat meetfouten meer mee gaan spelen.	Er zit volgens mij spanning in het materia de bovenkant wordt het samengedrukt e onderkant opgerekt.
3PBT 5	Ik denk dat Young's modulus zegt hoeveel kracht een materiaal aankan voordat het breekt.	Je zet een gewicht op een materiaal en dan zie je wat er gebeurt, lijkt me?	Nee, dit is de eerste keer dat ik zelf echt iets test.	4 Ik voel me wel zeker, maar ik weet niet of ik het goed uitleg.	Ik hoop dat het me helpt om dat hele 'modulus'-idee te begrijpen.	Het materiaal buigt in het midden, dat zie voor je als je er kracht op zet.
3PBT 6	Young's modulus is een stijfheidsmaat, maar ik weet niet goed wanneer je het precies gebruikt.	Door kracht op een balkje te zetten en te kijken hoeveel het buigt.	Nee, alleen wel eens gezien	3 Ik ben goed met formules, maar meten is nieuw.	Ik wil weten of de theorie overeenkomt met de praktijk.	Het materiaal vervormt elastisch, dus het maar breekt niet.
3PBT 7	Maybe how strong the material is?	You push and see how much it moves I guess	No, this is the first time	2. I don't really understand	I want to see what is happening	The strip bends
3PBT 8	Iets met stijfheid van een materiaal, maar ik weet niet precies wat het getal zegt.	Door kracht te zetten op iets en dan te meten hoeveel het doorbuigt.	Nee, dit is mijn eerste échte test.	2 Theorie vind ik vaag, ik hoop dat het straks duidelijker is.	Ik wil het eindelijk een keer in het echt zien, niet alleen in een tekening	Het buigt in het midden als je er kracht op

Table F3 Part Two - Participant Responses Continued

Theory_Q4: Confusing parts?	Theory_Q5: How would you explain the theory?	HandsOn_Q1: What did you learn?	HandsOn_Q2: Surprising behavior?	HandsOn_Q3: Misconceptions corrected?	HandsOn_Q4: Confidence now (1–5)
Alle maten waren in millimeters gegeven en moesten in meters, dat voelde gek, omdat het zulke kleine waardes werden.	Je legt een stripje materiaal op twee steunpunten en duwt in het midden. Dan meet je hoeveel het doorbuigt, en met een formule kan je daaruit afleiden hoe stijf het materiaal is. En een tekening maken, dat hielp mij echt.	Vooral hoe precies je moet zijn met meten. En dat het niet altijd zo rechtlijnig verloopt als op papier.	Ja, het buigt sneller dan ik dacht. En als je het een tijdje laat hangen, verandert de kracht een beetje. Dat wist ik niet.	Ja, ik dacht dat het allemaal super lineair zou zijn. Maar het materiaal verandert een beetje door de tijd en kracht, dus het is minder "perfect" dan ik had verwacht.	Een 5 denk ik, m'n begrip is wel beter geworden.
Ja! Vooral het omrekenen van mm naar meters en grammen naar Newtons. En die macht drie vond ik ook een beetje vaag.	Je legt een balkje op twee steunen en drukt in het midden. Dan meet je hoeveel het buigt, en daaruit kan je berekenen hoe stijf het materiaal is, Maar ik zou het liever tekenen of laten zien.	Dat meten best moeilijk is als je niet weet hoe het apparaat werkt. En dat je echt goed moet opletten hoe je dingen vasthoudt en afleest. Maar het werd wel duidelijker wat alles betekende.	Ja, ik had niet verwacht dat het zoveel boog met maar een beetje kracht. En dat het gewicht niet stabiel bleef, dat veranderde een beetje.	Ja, ik dacht dat die draaiknop vastzat en dat je hem niet kon verplaatsen.	Een 4. Door het te doen snap ik veel beter wat het nou echt is. Alleen de berekening blijft wel lastig.
Ja die eenheden en zo, en kg vs N is verwarrend.	Je legt een balkje neer en daar druk je op.	Dat het niet zo stabiel is als ik dacht.	Ja, het ging best snel doorbuigen.	k dacht dat kracht in kilo's was, maar dat klopt niet.	3. Ik snap het wel iets beter denk ik
iet echt verwarrend, wel even opletten dat alles in meters en Newtons staat.	Ik zou starten met een schets van de buigtest, uitleggen wat er fysiek gebeurt en pas daarna de formule erbij pakken.	Wat me opviel is dat de kracht bleef verschuiven, zelfs als ik even niets draaide. Ik weet niet waar dat door komt. Het materiaal had veel minder kracht nodig om te buigen dan ik had verwacht	Ik had het gevoel dat de onderste ligger misschien iets meebeweegt. Niet veel, maar het was lastig om zeker te zijn of dat punt echt vast stond. Daardoor begon ik te twijfelen of mijn metingen helemaal betrouwbaar waren.	Daardoor begon ik te twijfelen of mijn metingen helemaal betrouwbaar waren.	5. Door die onzekerheden snap ik nu het belang van reproduceerbaarheid wel echt beter.
Ja, ik twijfelde of ik de kracht in grammen of Newtons moest zetten.	Ik zou het laten zien met een balkje, en dan uitleggen dat je meet hoeveel het zakt bij kracht, en dat dat iets zegt over hoe stijf het materiaal is.	Nu snap ik beter waarom meten zo lastig is. Vooral het stripje op de juiste plek leggen is gepruts. Als hij scheef ligt, klopt je meting niet.	De krachtwaarde daalde een beetje nadat ik gestopt was met draaien. Eerst dacht ik dat dat een fout was, maar volgens mij komt dat doordat het materiaal een beetje terugveert.	Ik dacht dat alles stabiel zou blijven als je stopte met draaien, maar blijkbaar kunnen er gewoon nog dingen in het materiaal gebeuren.	4 Ik snap nu veel beter wat die modulus doet en hoe belangrijk het is om alles goed te meten.
Ik ging bijna de mist in met die derde machts	Ik zou beginnen met uitleggen dat het over elastische vervorming gaat, en dan een testopstelling tekenen.	Het afmeten van de afstand tussen de liggers met de schuifmaat was moeilijker dan ik had verwacht. Je moet echt goed kijken waar je meet, en het voelde niet altijd super stabiel.	De kracht daalde iets na het draaien. Dat had ik niet verwacht; ik dacht dat het stabiel zou blijven.	Ik dacht altijd dan 1 keer meten genoeg was, maar het is me nu wel duidelijk dat dit soort metingen niet allemaal meewerken dus je moet meer metingen op precies dezelfde manier proberen uit te voeren.	4 Ik snap nu hoe belangrijk nauwkeurigheid is bij fysiek meten.
The formula was hard, I don't think I did the units right haha.	Maybe with an example, or a drawing	The strip was hard to place straight.	After I stopped turning the force went down. I thought it stayed the same	I still don't understand why it still moved	3. I see better what is happening, but I don't understand what the modulus means.
De eenheden zijn echt lastig: mm naar meter, gram naar Newton.	Ik zou het gewoon laten zien met een schets en uitleggen wat er gebeurt bij elke stap.	Het was even prutsen om dat stripje goed te leggen, vooral omdat je het van de zijkant moet doen. Maar toen alles eenmaal goed zat, begon het wel te klikken.	Het was heel makkelijk om het materiaal te vervormen, veel makkelijker dan ik dacht. Maar je voelde het ook niet heel goed of je het materiaal al aan het doorbuigen was.	Nadat je stopt met draaien blijven er dingen gebeuren, ik dacht eigenlijk dat de situatie gewoon een soort van zou bevroren zou zijn ofzo?	4. Het er mee bezig zijn hielp heel erg omdat je precies zijn welke waardes waar vandaan komen.

...pens ...ce?	Theory_Q2: Understand deflection?	Theory_Q3: Confidence in result
...drukt of ...t zet. In ...er van	Ja, dat is hoe ver het materiaal doorbuigt in het midden. Dus letterlijk hoeveel het afwijkt van de rechte lijn.	Best wel zeker, ik zou een 4 geven. Ik ben best zorgvuldig door die formule heengegaan haha, het sprak opzich best voor zichzelf.
...den. En	Ja, nu wel. Dat is gewoon hoe ver het materiaal doorzakt in het midden.	een 2 of 3. Ik snapte de formule op zich wel, maar ik vond het lastig met al die eenheden. En ik ben bang dat ik iets fout heb omgerekend.
	Een beetje, is de afstand die het zakt?	2 Ik heb gewoon ingevuld wat er stond.
...al, aan ...n aan de	De doorbuiging van het materiaal.	5. Moet wel kloppen
...je ook	Beetje. Het is de buiging, maar ik weet nog niet hoe dat precies in de formule past.	3 of 4 Ik snapte wat ik moest invullen, maar of het resultaat klopt weet ik niet zeker.
...buigt	Ja, dat is hoe ver het buigt in het midden.	4. De formule ging goed, maar afronding en eenheden zijn tricky.
	I think so, it is how much it moves down right?	2. I used a calculator but I don't understand why the number is important
...zet.	Ja, het is hoeveel het afwijkt in het midden van het balkje.	3. Ik heb alles omgerekend, maar ik weet nog niet echt wat ik ermee kan.

HandsOn_Q5: Start with theory or physical?	HandsOn_Q6: Final thoughts
Ik zou beginnen met de fysieke test. Dan zie je meteen wat er gebeurt en waarom je die formule nodig hebt. Het maakt de theorie logischer.	Ik vond het apparaat heel nice, bij de theorie doe je maar 1 berekening, om te kijken of je kan rekenen. Maar bij de fysieke proef wordt ook duidelijk dat het in de realiteit niet zo werkt, dat er veel meer bij komt kijken. Alleen al op meer momenten de meting doen enzo.
Ik zou beginnen met de test. Dan zie je meteen wat er gebeurt en dan snap je de theorie makkelijker daarna. Alleen zou ik er ook meteen een uitleg bij doen, anders weet je niet goed wat je moet meten.	het was eigenlijk best leuk Alleen zou ik het fijner vinden als er pijltjes op het apparaat staan omdat je die knop meteen de verkeerde kant op draait. Ik vond het ook lastig om precies de afstand tussen die liggers te meten. Ik wist soms niet zeker of ik het goed deed. Maar het hielp wel om het echt vast te houden en uit te proberen.
Eerst fysiek, dan heb je beeld erbij.	Het apparaat wiebelde wel een beetje. Ik vond het lastig om de schuifmaat goed af te lezen en goed vast te houden, best onhandig.
Fysiek eerst. Dan zie je gelijk waar het écht fout kan gaan.	Iets van visuele tekentjes of uitleg zou wel fijn zijn voor het gebruik denk ik.
Fysiek eerst. Dat geeft context voor de formule.	Zou handig zijn als het stripje automatisch goed zou liggen, en als er een soort 'klik' of aanduiding was voor wanneer je echt moet meten. Het belang van goed meten is me wel heel duidelijk geworden.
Fysiek eerst. Dan weet je wat er fout kan gaan.	De punten waar je precies moet meten zou fijn zijn, sowieso iets meer aanduidingen op het ding zelf.
Maybe physical first, but I still need help	I thought it was fun to do, but I don't know when to stop or write down the measurements.
Misschien eerst de formule laten zien en het dan fysiek doen om te kijken waar alle waardes nou precies bij horen in de realiteit. Dat gaf mij wel perceptie iig.	Heel waardevol. Misschien zou een kort lijstje met waar moet je op letten tijdens meten

F4 - ST Consent Form

TU Delft – Informed Consent Form

Title of Research Project: *Understanding Material Properties in Engineering Education*

Researcher: Wouter Huisman, MSc Integrated Product Design, TU Delft

Participant Information

You are invited to take part in a research study that explores how students learn about material properties using hands-on and analytical testing methods. The study includes activities such as performing a 3-point bending test using a 3D-printed device and several intuitive material identification tests using touch, sound, temperature, and weight. You will also be asked to answer a few short questions before and after the tests to reflect on your understanding and experience.

Your participation is voluntary. You can withdraw from the study at any time without giving a reason. The study will take approximately 45–60 minutes.

No personally identifiable information (such as your name or contact details) will be collected. Data from your responses and test results will be stored securely, anonymised, and may be used for academic publications, presentations, and teaching materials. Only the research team will have access to the full data. Data will be stored for up to 10 years, according to TU Delft research data guidelines.

The tests are not CE-certified. There are minimal risks involved. The equipment used is safe, manually operated, and has been pre-tested. Instructions will be provided, and the researcher will supervise all activities.

If you have questions about the study, please contact: Wouter Huisman,

Consent

Please tick the boxes to confirm:

☐ I have read and understood the information above.

☐ I voluntarily agree to participate in this study.

☐ I understand I can withdraw at any time without explanation.

☐ I agree that anonymised data from this study may be used for academic publication, education, or further research.

☐ I give permission for my anonymised data to be archived for future research and teaching purposes.

Name of Participant: ________________________

Signature: _____________________

Date: _________________________

Researcher Declaration:

I, the undersigned, confirm that I have provided a clear explanation of the study and answered any questions to the best of my ability.

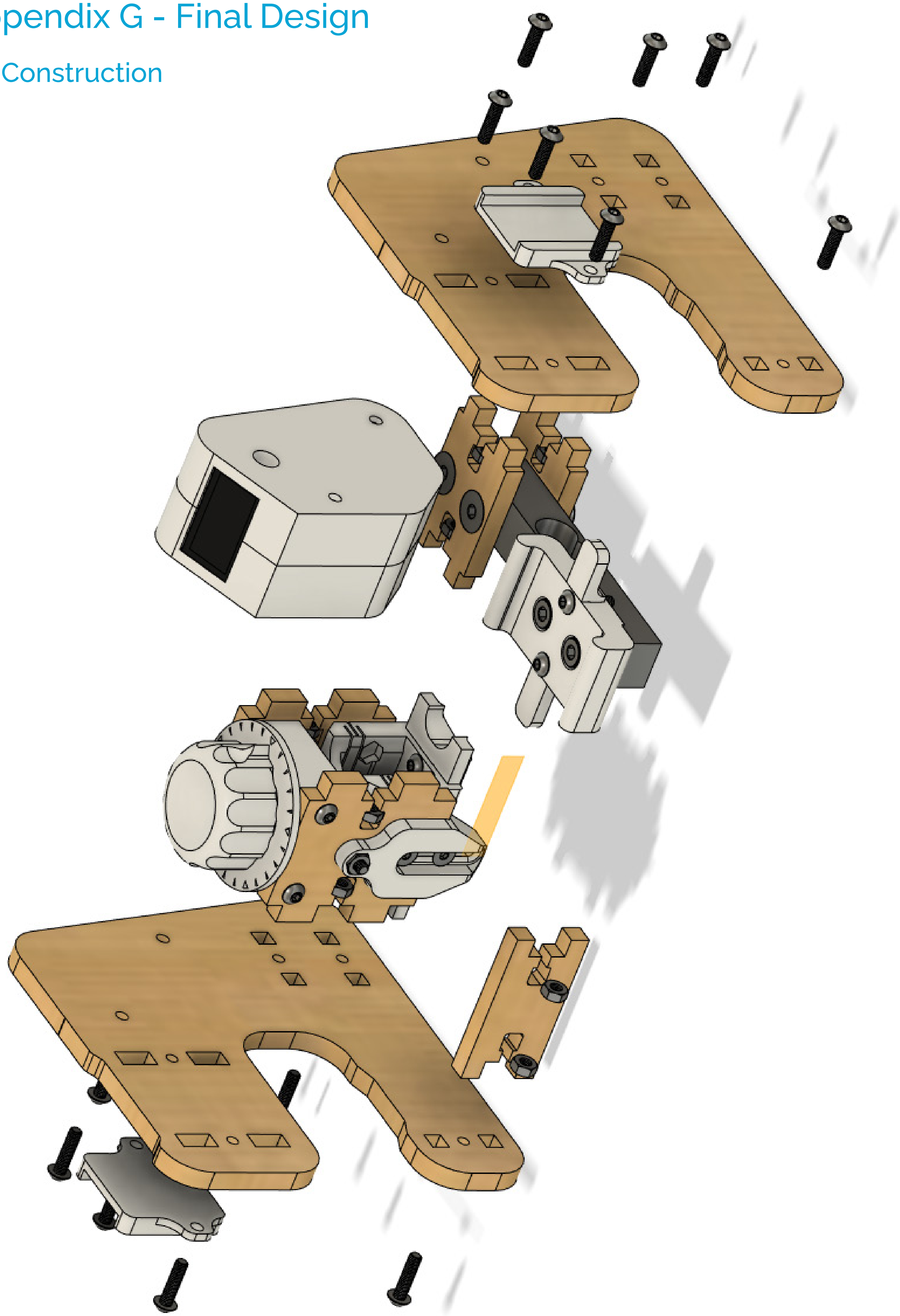
Researcher Name: ________________________

Signature: _____________________

Date: _________________________

Appendix G - Final Design

G.1 Construction



G.2 Bill of Materials

Table G.2 - Bill of Materials

Device	Part no.	Part Name	Assembly	Description	Material	Method
Structured Track **3 Point Bend Test**	P01	Housing Plate	Housing	Two plates with different engravings	Populieren 5mm	Lasercutting
	P02	Load cell Plate	Housing	Plates that hold Load cell	Populieren 5mm	Lasercutting
	P03	Support Plate	Housing	Plate for extra rigidity	Populieren 5mm	Lasercutting
	P04	Measuring Flange	Housing	Part to hold callipers for measuring	PLA	3D Printing
	P05	Press Assembly Plate	Press Assembly	Mounting plate for press assembly	Populieren 5mm	Lasercutting
	P06	Indenter	Press Assembly	Presses sample	PLA	3D Printing
	P07	Guiding Part	Press Assembly	Guides indenter	PLA	3D Printing
	P08	Indenter Measuring Part	Press Assembly	Rests callipers for measuring	PLA	3D Printing
	P09	Bearing Housing	Press Assembly	Houses Bearings	PLA	3D Printing
	P10	Nonius	Press Assembly	Allows measuring of indenter movement	PLA	3D Printing
	P11	Knob	Press Assembly	Allows easier rotation of Indenter Bolt	PLA	3D Printing
	B01	Bearing	Press Assembly	608zz Skateboard bearing	Steel	BUY
	B02	M8 Steel Hex Screw	Press Assembly	M8x50 10.9 high strength	Steel	BUY
	B03	M8 Steel Nut	Press Assembly	M8 High strength	Steel	BUY
	B04	M3 Countersunk hex	Press Assembly	m3x12 Alligns indenter assembly	Steel	BUY
	B05	Microprocessor	Electronics	Seeeduino Xiao	-	BUY
	B06	Load Cell	Electronics	TAL220 10kg straight bar load cell	Steel	BUY
	B07	Load Cell Amplifier	Electronics	hx711 module	-	BUY
	B08	Screen	Electronics	OLED-LCD 0,96 inch display ASIN: B0CTMKZJ5L	-	BUY
	P12	Left Electronics Housing	Electronics	Mounts screen, microprocessor and amplifier	PLA	3D Printing
	P13	Right Electronics Housing	Electronics	Mounts screen, microprocessor and amplifier	PLA	3D Printing
	P14	Anvil	Electronics	Holds sample	PLA	3D Printing
	P15	Anvil Measuring Part	Electronics	Rests callipers for measuring	PLA	3D Printing
	B09	Wiring	Electronics	10cm Female to Female cable (cut in half)	-	BUY
	B10	M5 Countersunk hex	Electronics	M5x8 Steel countersunk hex screw	Steel	BUY
	B11	M4 bolt	Electronics	M4x20 steel hext screw	Steel	BUY
	B12	M3 screw	Mounting Hardware	Mounts everything	Steel	BUY
	B13	M3 Nut	Mounting Hardware	Mounts everything	Steel	BUY
Intuitive Track **LED Test**	P16	LED Housing	LED	Houses all components	PLA	3D Printing
	P17	Front Plate	LED	Covers Housing, has engraved instructions	5mm Populieren	Lasercutting
	B14	Test Clip	LED	Allows attachment to samples. cut in half	-	BUY
	B15	LED	LED	Red LED	-	BUY
	B16	Resistor	LED	150Ω Resistor	-	BUY
	B17	USB-C Port	LED	USB-C Female to power port	-	BUY
	B12	M3 screw	LED	Mounts everything	Steel	BUY
Heating Test	P18	Heating Housing	Heating	Houses all components	PLA	3D printing
	P19	Front Plate	Heating	Covers Housing, has engraved instructions	5mm Populieren	Lasercutting
	B18	Heating Element	Heating	5v PTC 40 degrees heating element	-	BUY
	B17	USB-C Port	Heating	USB-C Female to power port	-	BUY
	B12	M3 screw	Heating	Mounts everything	Steel	BUY
Density Test	B19	Scale	Density	1kg precision Scale	-	BUY
	B20	Precision Tweezeres	Density	Precision tweezers with small tip	-	BUY
	B21	Container	Density	Small container to hold water	-	BUY
Magnet Test	B22	Magnet	Magnet	Neodymium Magnet	Neodymium	BUY
Scratch Test	B23	Scratch Nail	Scratch	Hardened Steel Nail	Steel	BUY
Storage Box	P20	Housing	Storage	Storage Box	PLA	3D Printing
	P21	Hinge	Storage	Hinge for lid	PLA	3D Printing
	P22	Lid	Storage	Cover Lid with engraving of 3 tests	3mm Populieren	Lasercutting
	B12	M3 screw	Storage	Mounts everything	Steel	BUY

uantity	One off	Bulk	Total OO	Total B	[g] OR [mm^2]	Material Cost pp	Source	Source Bulk
2	€ 0,27	€ 0,27	**€ 0,53**	**€ 0,53**	10800	€ 0,13		
2	€ 0,02	€ 0,02	**€ 0,05**	**€ 0,05**	1000	€ 0,01		
1	€ 0,01	€ 0,01	**€ 0,01**	**€ 0,01**	800	€ 0,01		
2	€ 0,10	€ 0,10	**€ 0,19**	**€ 0,19**	2,8	€ 0,05		
2	€ 0,04	€ 0,04	**€ 0,08**	**€ 0,08**	1640	€ 0,02		
1	€ 0,24	€ 0,24	**€ 0,24**	**€ 0,24**	14,26	€ 0,24		
2	€ 0,14	€ 0,14	**€ 0,27**	**€ 0,27**	4,03	€ 0,07		
2	€ 0,04	€ 0,04	**€ 0,08**	**€ 0,08**	1,21	€ 0,02		
1	€ 0,11	€ 0,11	**€ 0,11**	**€ 0,11**	6,37	€ 0,11		
1	€ 0,04	€ 0,04	**€ 0,04**	**€ 0,04**	2,29	€ 0,04		
1	€ 0,09	€ 0,09	**€ 0,09**	**€ 0,09**	5,31	€ 0,09		
2	€ 0,75	€ 0,60	**€ 1,50**	**€ 1,20**			https://www.123-3d.nl/123-3D-Kogellager-608	
1	€ 0,46	€ 0,16	**€ 0,46**	**€ 0,16**			https://www.rvsn	https://rvsland.nl/rvs-zeskar
3	€ 0,36	€ 0,07	**€ 1,08**	**€ 0,21**			https://www.rvsn	https://rvsland.nl/rvs-moere
4	€ 0,23	€ 0,02	**€ 0,92**	**€ 0,08**			https://www.rvsn	https://schroevengroothanc
1	€ 6,28	€ 6,16	**€ 6,28**	**€ 6,16**			https://www.kiwi-electronics.com/nl/seeeduin	
1	€ 2,37	€ 2,37	**€ 2,37**	**€ 2,37**			https://www.amazon.nl/Reland-Sun-Druksensc	
1	€ 3,17	€ 3,17	**€ 3,17**	**€ 3,17**			https://www.amazon.nl/AZDelivery-SSD1306-c	
1	€ 6,99	€ 2,71	**€ 6,99**	**€ 2,71**				
1	€ 0,23	€ 0,23	**€ 0,23**	**€ 0,23**	13,49	€ 0,23		
1	€ 0,21	€ 0,21	**€ 0,21**	**€ 0,21**	12,15	€ 0,21		
1	€ 0,16	€ 0,16	**€ 0,16**	**€ 0,16**	9,48	€ 0,16		
2	€ 0,03	€ 0,03	**€ 0,05**	**€ 0,05**	0,79	€ 0,01		
4	€ 0,05	€ 0,04	**€ 0,20**	**€ 0,16**			https://www.tinytronics.nl/en/cables-and-conr	
4	€ 0,23	€ 0,04	**€ 0,92**	**€ 0,16**			https://www.rvsn	https://rvsland.nl/din7991-a
2	€ 0,23	€ 0,04	**€ 0,46**	**€ 0,08**				https://rvsland.nl/inbusbout
27	€ 0,12	€ 0,03	**€ 3,24**	**€ 0,81**				https://www.techwinkel.nl/
16	€ 0,12	€ 0,01	**€ 1,92**	**€ 0,08**				https://www.techwinkel.nl/
			One Off	*Bulk (75 pc)*				
ructured		Tota	**€ 31,86**	**€ 19,70**				
1	€ 0,34	€ 0,34	**€ 0,34**	**€ 0,34**	20,03	€ 0,34		
1	€ 0,05	€ 0,05	**€ 0,05**	**€ 0,05**	4005	€ 0,05		
1	€ 3,75	€ 0,38	**€ 3,75**	**€ 0,38**				https://opencircuit.nl/produ
1	€ 0,17	€ 0,15	**€ 0,17**	**€ 0,15**				https://www.allekabels.nl/le
1	€ 1,64	€ 0,16	**€ 1,64**	**€ 0,16**				
1	€ 4,50	€ 1,80	**€ 4,50**	**€ 1,80**				https://www.amazon.nl/Gre
4	€ 0,12	€ 0,03	**€ 0,48**	**€ 0,12**				https://www.techwinkel.nl/
			One Off	*Bulk (75 pc)*				
	LED	Total	**€ 10,93**	**€ 3,00**				
1	€ 0,33	€ 0,33	**€ 0,33**	**€ 0,33**	19,28	€ 0,33		
1	€ 0,05	€ 0,05	**€ 0,05**	**€ 0,05**	4005	€ 0,05		
1	€ 2,75	€ 2,75	**€ 2,75**	**€ 2,75**				https://eu.robotshop.com/r
1	€ 4,50	€ 1,80	**€ 4,50**	**€ 1,80**				https://www.amazon.nl/Gre
8	€ 0,12	€ 0,03	**€ 0,96**	**€ 0,24**				https://www.techwinkel.nl/
			One Off	*Bulk (75 pc)*				
	Heatin	Total	**€ 8,59**	**€ 5,17**				
1	€ 8,50	€ 8,50	**€ 8,50**	**€ 8,50**				https://www.bol.com/nl/nl/
1	€ 5,35	€ 0,89	**€ 5,35**	**€ 0,89**				https://www.bol.com/nl/nl/
1	€ 11,99	€ 0,70	**€ 11,99**	**€ 0,70**				https://www.amazon.nl/KLY
			One Off	*Bulk (75 pc)*				
	Densit	Total	**€ 25,84**	**€ 10,09**				
1	€ 5,29	€ 0,08	**€ 5,29**	**€ 0,08**				https://www.amazon.nl/ma
			One Off	*Bulk (75 pc)*				
	Magne	Total	**€ 5,29**	**€ 0,08**				
1	€ 3,51	€ 0,04	**€ 3,51**	**€ 0,04**				https://www.praxis.nl/ijzerv
			One Off	*Bulk (75 pc)*				
	Scratcl	Total	**€ 3,51**	**€ 0,04**				
1	€ 1,00	€ 1,00	**€ 1,00**	**€ 1,00**	58,88	€ 1,00		
2	€ 0,04	€ 0,04	**€ 0,08**	**€ 0,08**	1,17	€ 0,02		
1	€ 0,10	€ 0,10	**€ 0,10**	**€ 0,10**	8010	€ 0,10		
6	€ 0,12	€ 0,03	**€ 0,72**	**€ 0,18**				https://www.techwinkel.nl/
			One Off	*Bulk (75 pc)*				
	Storag	Total	**€ 1,90**	**€ 1,36**				
tuitive		Tota	**€ 56,05**	**€ 19,73**				
			One off	*Bulk (75pc)*				
ll Setup Total			**€ 87,91**	**€ 39,43**				

FILAMENT PRICE PER KG (Bulk Price)	Price per gram
€ 16,99	€ 0,02
Lasercut wood Price per sheet 1100x800	**Price per mm^2**
€ 10,00	€ 0,00
1070x760 is useable	

Appendix H - Education Validation

Appendix H1 - Full Study

H.1.1 - Introduction

After the workshops were developed, a small validation was carried out to see how students responded to the setup in practice. The goal wasn't to measure learning outcomes in a formal sense, but to observe whether the workshops triggered the kinds of reasoning they were designed to support. The workshops can be found in Appendices X.2.1 and X.2.2.
Both workshops were based on the structure of the UPE course, where students are expected to engage with a problem intuitively before receiving formal theory. The design relied on Productive Failure principles, where the initial struggle is meant to create a need for deeper understanding. This validation focused on capturing how students approached the tasks, what kind of reasoning they showed, and how that changed once tools or theory were introduced.

H.1.2 Methods

Three student (first year IDE) groups participated in the study:
- Group A: 1 student working individually
- Group B: 2 students working collaboratively
- Group C: 2 students, with one noticeably less active

Each group completed both workshops:
1. Workshop 1: Students began by sorting unknown materials intuitively, then applied a series of property tests (magnetism, scratch, conductivity, thermal feel, and density).
2. Workshop 2: Students were asked to estimate how many people could stand on a bench without excessive bending, used a scale model to experiment, and later received a bending formula to reflect on their results.

All sessions were observed in real-time. Notes were taken on student behaviour, verbal reasoning, and interaction with materials and tools. No scores or performance outcomes were recorded. The focus was on observable shifts in reasoning and engagement.

H.1.3 Results

Workshop 1 – Material Identification (Appendix X.3.1)
- Most students began with guesses based on visual and tactile cues (e.g. weight, texture, surface finish).
- Reasoning became more structured after the introduction of test tools.
- The density test marked a clear shift for all groups. At that point, students moved from uncertain intuition to data-based conclusions.
- Students began referring to measurable properties instead of just how something looked or felt.
- Group B actively built on each other's observations. Group C, in contrast, remained disconnected. one student carried the process while the other barely contributed.

Workshop 2 – Bench Deflection (Appendix X.3.2)
- Initial estimates were vague and not based on any clear logic.
- The scale model helped students develop a more accurate sense of how loading affected bending. Group B identified creep on their own. Group A recognised the nonlinear increase in deflection.
- Once the bending formula was introduced, all groups revisited their earlier assumptions. Most used the equation not just to calculate, but to validate what they had already observed.
- Some students reflected on their testing approach and mentioned that averaging multiple measurements would have led to better accuracy. a realisation that only came after hearing the extra theory.
- In Group C, limited engagement continued, and little conceptual progress was visible beyond surface-level activity.

H.1.4 Strengths and Limitations

Strengths:

- Student behaviour showed visible shifts from surface-level intuition to more structured reasoning.
- In several cases, students used the provided tools or formulas not just to "get the answer," but to make sense of earlier results.
- Observing both workshops gave insight into how students test, interpret, and revise their thinking across different problem types.

Limitations:

- The sample size was very small (five participants in total), so findings are not generalisable.
- No formal learning gains were measured (e.g. through pre/post tests). Conclusions rely on interpretation of observed behaviour.
- The students involved had already been exposed to most of the theory earlier in the course. As a result, some of the intended "productive struggle" may have been reduced. Their reasoning might have been influenced more by recall than by exploration.

H.1.5 Discussion

The validation showed that both workshops helped students move from assumptions to structured reasoning. In Workshop 1, students first sorted materials based on intuition, then refined their classifications using a series of physical tests: magnetism, scratch resistance, conductivity, thermal feel, and density. Especially he density test marked a shift toward more confident, evidence-based conclusions.

In Workshop 2, students explored bench deflection using a three-point bending setup. They experimented with force and deflection using a scale model before receiving the theoretical formula. Most groups used this process to reflect on earlier guesses and reason about the role of stiffness and geometry.
Although students had already encountered much of the theory in their course, the hands-on tests and tools still led to useful insights, especially when contradictions or unexpected results forced them to reconsider their thinking.

H.1.6 Conclusions

The workshops provided a practical structure for reasoning development through exploration. While the prior knowledge of the students limited the "struggle" intended by the Productive Failure approach, the format still led to meaningful engagement.

All five physical tests in Workshop 1 supported material recognition, with students showing clearer reasoning as they moved from tactile impressions to measurable properties. The density test was especially decisive.
In Workshop 2, the three-point bending setup proved valuable not only as a test tool but as a reasoning aid. Students used it to explore the effect of force, span, and cross-section, even when their measurements were imperfect. The validation confirmed that the physical tools supported theoretical content in observable outcomes.

Appendix H2 Workshops
H2.1 - Workshop 1: Intuitive

Workshop
Materiaal Determinatie

Materiaalscheiding

Notes:
Uitleg Blends

10:00

Je loopt stage bij een duurzaam ontwerpbureau. Je krijgt de opdracht:
"Kun jij deze materialen sorteren, zodat ze opnieuw gebruikt of goed gerecycled kunnen worden?"

Voor je staat een bak met restmaterialen. Geen labels, geen datasheets. Je weet alleen:

- Het zijn zuivere materialen (dus géén blends)
- Ze behoren tot: metalen, kunststoffen of houtsoorten

1: Sorteer de materialen zo ver mogelijk, waarom heb je ze zo gegroepeerd?

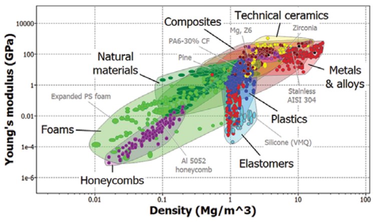
2: Hoe zou je meer te weten kunnen komen over deze materialen om ze verder te kunnen sorteren?

Uitleg Materiaaleigenschappen

Materialen hebben **eigenschappen** die bepalen hoe ze zich gedragen in verschillende situaties. Denk aan:

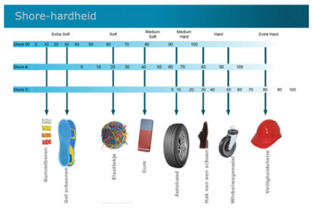
- Hoe hard iets is (**oppervlaktehardheid**)
- Hoe goed het warmte of stroom geleidt (**Thermische en Elektrische geleiding**)
- Hoe het reageert op een magneet (**magnetisme**)

Elk materiaal heeft unieke eigenschappen die daarom gebruikt kunnen worden om materialen te onderscheiden.

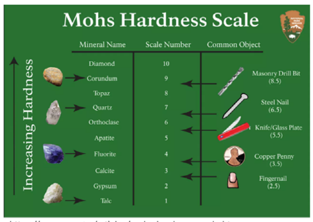


Uitleg Oppervlakteharheid

Laat zien hoe **makkelijk een materiaal aan de buitenkant beschadigt**, bijvoorbeeld door krassen. Metalen of harde kunststoffen (zoals PMMA) zijn moeilijker te bekrassen. Zachtere materialen zoals hout of polypropyleen (PP) beschadigen sneller. Deze eigenschap helpt om groepen materialen van elkaar te onderscheiden.



https://www.almotion.nl/techindex/shore-hardheid/ohs



https://www.nps.gov/articles/mohs-hardness-scale.htm

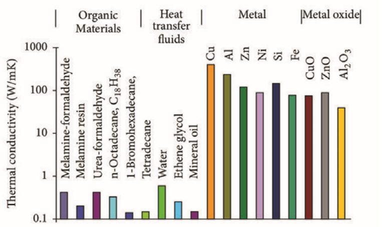
Uitleg Thermische geleiding

Zegt hoe snel een materiaal **warmte verspreidt**. Metalen geleiden warmte goed, omdat dezelfde vrije elektronen die stroom vervoeren ook energie kunnen meenemen.

Daarom voelt metaal koud aan: het trekt snel warmte uit je hand.

Kunststoffen geleiden warmte veel slechter. Ze geven warmte langzaam door via trilling van de moleculen → ze voelen warm of neutraal aan.

Vergelijking: Een metalen lepel in hete thee wordt snel heet. Een plastic lepel blijft lang koel.

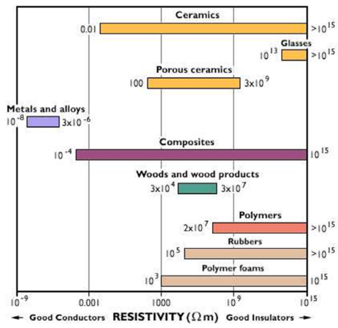


https://www.researchgate.net/figure/Thermal-conductivity-comparison-of-common-polymers-liquids-and-solids-64_fig1_324058800

Uitleg Elektrische Geleidbaarheid

Geeft aan of een materiaal **stroom** kan geleiden. Metalen hebben vrije elektronen die zich makkelijk kunnen verplaatsen → stroom kan erdoor. Kunststoffen en hout hebben dat niet → ze zijn **isolatoren**.

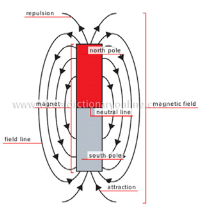
Vuistregel: materialen die goed elektrische stroom geleiden, geleiden vaak ook warmte goed, omdat beide via dezelfde vrije elektronen gaan.



https://www.lehigh.edu/~amb4/wbi/kwardlow/conductivity.htm

Uitleg Magnetisme

Geeft aan of een materiaal **aangetrokken** wordt door een **magneet**. Alleen sommige metalen zijn **ferromagnetisch**, zoals ijzer, staal en nikkel. Die hebben een structuur waarin kleine magnetische gebieden (domeinen) zich kunnen uitlijnen. Andere metalen zoals aluminium en koper zijn **niet ferromagnetisch** en reageren dus niet op een magneet.



https://www.visualdictionaryonline.com/science/physics-electricity-magnetism/magnetism.php

Materiaalscheiding

Notes:
Uitleg magnetisme, elektrische geleiding en warmtegeleiding.

20:00

Je mag nu vier eenvoudige testjes uitvoeren op de materialen:

- **Magneettest**
- **Krastest**
- **Elektrische geleidingstest**
- **Warmtetest**

3: Sorteer nu de rest van de materialen.

4: Zijn er materialen waar je over twijfelt?

5: Bedenk een manier om die materialen te bevestigen.

Categorie	Materiaal	Hardheid	Elektrische geleiding	Warmtegeleiding	Magnetisch
Hout	Beuken	Medium	Niet geleidend	Zeer laag	Nee
Hout	Eiken	Medium	Niet geleidend	Zeer laag	Nee
Hout	Vurenhout	Laag	Niet geleidend	Zeer laag	Nee
Hout	Bamboe	Medium	Niet geleidend	Zeer laag	Nee
Hout	Populieren	Laag	Niet geleidend	Zeer laag	Nee
Metaal	Aluminium	Medium	Geleidend	Hoog	Nee
Metaal	RVS (304)	Hoog	Geleidend	Medium	Soms*
Metaal	Koper	Medium	Zeer goed geleidend	Zeer hoog	Nee
Metaal	Messing	Medium	Goed geleidend	Hoog	Nee
Metaal	IJzer	Hoog	Zeer goed geleidend	Hoog	Ja
Kunststof	PP	Zeer laag	Niet geleidend	Zeer laag	Nee
Kunststof	PE	Zeer laag	Niet geleidend	Zeer laag	Nee
Kunststof	HDPE	Zeer laag	Niet geleidend	Zeer laag	Nee
Kunststof	ABS	Laag	Niet geleidend	Laag	Nee
Kunststof	PMMA	Laag	Niet geleidend	Laag	Nee
Kunststof	PC	Laag	Niet geleidend	Laag	Nee
Kunststof	PVC (Hard)	Medium	Niet geleidend	Zeer laag	Nee
Kunststof	PS	Medium	Niet geleidend	Laag	Nee

Uitleg Dichtheid

Dichtheid vertelt je hoeveel **massa** er zit in een bepaald **volume** van een materiaal.

$$Dichtheid\ [\rho] = \frac{Massa\ [g]}{Volume\ [cm^3]}$$

Twee voorwerpen kunnen even groot zijn, maar **de één voelt zwaarder**
→ die heeft **hogere dichtheid**

Substance	Density, g/mL
Hydrogen (gas)	0.000089
Carbon dioxide (gas)	0.0019
Cork	0.21
Oak wood	0.71
Ethyl alcohol	0.79
Water	1.00
Magnesium	1.74
Table salt	2.16
Sand	2.32
Aluminum	2.70
Iron	7.86
Copper	8.92
Lead	11.34
Mercury	13.59
Gold	19.3

https://www.researchgate.net/figure/Illustrate-the-densities-of-some-common-substances_tbl4_295076524

Materiaalscheiding

Notes:
Uitleg Dichtheid

10:00

Je mag nu de dichtheid van de materialen bepalen met de Archimedes-methode (lees instructies op het materialenbakje).

$$Dichtheid\ [\rho] = \frac{Massa\ [g]}{Volume\ [cm^3]}$$

6: Bepaal nu de laatste materialen

7: Zijn er materialen die dichter bij elkaar lagen dan je oorspronkelijk dacht?

Categorie	Materiaal	Hardheid	Elektrische geleiding	Warmtegeleiding	Magnetisch	Dichtheid (g/cm³)
Hout	Beuken	Medium	Niet geleidend	Zeer laag	Nee	0.72 – 0.75
Hout	Eiken	Medium	Niet geleidend	Zeer laag	Nee	0.70 – 0.77
Hout	Vurenhout	Laag	Niet geleidend	Zeer laag	Nee	0.45 – 0.50
Hout	Bamboe	Medium	Niet geleidend	Zeer laag	Nee	0.60 – 0.80
Hout	Populieren	Laag	Niet geleidend	Zeer laag	Nee	0.35 – 0.45
Metaal	Aluminium	Medium	Geleidend	Hoog	Nee	2.70
Metaal	RVS (304)	Hoog	Geleidend	Medium	Soms*	7.80 – 8.00
Metaal	Koper	Medium	Zeer goed geleidend	Zeer hoog	Nee	8.90
Metaal	Messing	Medium	Goed geleidend	Hoog	Nee	8.40 – 8.70
Metaal	IJzer	Hoog	Zeer goed geleidend	Hoog	Ja	7.85
Kunststof	PP	Zeer laag	Niet geleidend	Zeer laag	Nee	0.90 – 0.91
Kunststof	PE	Zeer laag	Niet geleidend	Zeer laag	Nee	0.92 – 0.96
Kunststof	HDPE	Zeer laag	Niet geleidend	Zeer laag	Nee	0.94 – 0.97
Kunststof	ABS	Laag	Niet geleidend	Laag	Nee	1.02 – 1.05
Kunststof	PMMA	Laag	Niet geleidend	Laag	Nee	1.18 – 1.20
Kunststof	PC	Laag	Niet geleidend	Laag	Nee	1.20 – 1.22
Kunststof	PVC (Hard)	Medium	Niet geleidend	Zeer laag	Nee	1.30 – 1.45
Kunststof	PS	Medium	Niet geleidend	Laag	Nee	1.04 – 1.06

Materiaalscheiding

05:00

8: Welke test gaf je uiteindelijk het meeste inzicht?

9: Waar zat je in het begin fout, en wat liet je dat inzien?

10: Wat zou je de volgende keer anders doen als je onbekende materialen moet analyseren?

Appendix H2 Workshops

H2.2 - Workshop 2: Structured

Workshop
Elasticiteitsmodulus

Oktoberfest Bankje

10:00

Een bankje op het ID Kafé Oktoberfest is kromgetrokken. De verhuurder weigert de borg terug te geven. Jouw taak: achterhalen hoeveel mensen er op een bankje mogen staan zonder dat het te ver doorbuigt.

Situatie:

- Bank: 2200 mm lang, 250 mm breed, 30 mm dik
- Afstand tussen de poten: 1800 mm
- Materiaal: hout (onbekende soort)

1: Bij hoeveel studenten buigt het de bank 10mm door? Hoe ben je daar op uit gekomen?

Oktoberfest Bankje

- Wat dacht je dat de grootste invloed had
- Wat zou je willen meten of weten om zek

https://eventrentall.nl/product/2x-bier-bankjes/

Uitleg 3 punts buigproef

F= kracht op het midden van de balk [N]

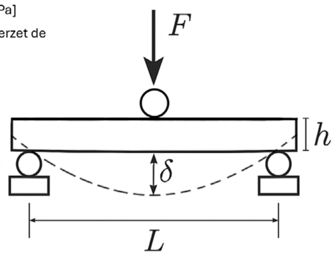
L = afstand tussen de steunpunten (spanwijdte) [MM]

E = elasticiteitsmodulus → hoe stijf is het materiaal [MPa]

I = traagheidsmoment van de doorsnede → hoe sterk verzet de doorsnede zich tegen buiging. [mm^4]

$$I = \frac{bh^3}{12}$$

$$E = \frac{FL^3}{48I\delta}$$



Oktoberfest Bankje

09:59

Nu krijg je toegang tot een schaalmodel van het bankje en het testapparaat.

2: Gebruik het apparaat om meerdere keren te kijken hoe ver het schaalmodel doorbuigt bij een belasting van 3kg. Wat valt je op?

Hier komt nog een afbeelding van mijn apparaat wat het schaalmodel doorbuigt.

https://eventrentall.nl/product/2x-bier-bankjes/

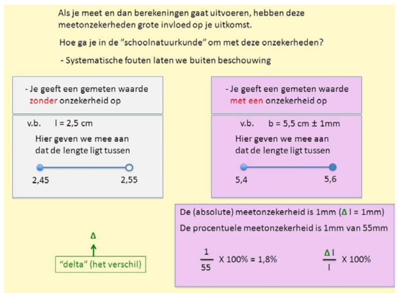
Uitleg Meetonzekerheden

Metingen zijn nooit perfect. Er zit altijd een beetje variatie in door:

- kleine fouten in het aflezen van metingen of positioneren van de samples.
- lichte verschillen in hoe de kracht wordt aangebracht
- gevoeligheid van het apparaat

Door **meerdere metingen te doen en het gemiddelde te nemen,** krijg je een veel betrouwbaarder resultaat.

Eén meting zegt iets, maar een gemiddelde zegt veel meer.
Zo weet je zekerder wat de echte relatie is tussen kracht en doorbuiging.



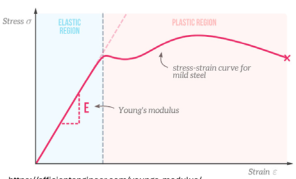
Oktoberfest Bankje

10:00

Nu krijg je toegang tot een schaalmodel van het bankje en het testapparaat.

3: Wat is de elasticiteitsmodulus van het schaalmodel?

$$E = \frac{FL^3}{48I\delta}$$



https://efficientengineer.com/youngs-modulus/

https://eventrentall.nl/product/2x-bier-bankjes/

Oktoberfest Bankje

10:00

Ga er vanuit dat het bierbankje dezelfde E-Modulus heeft als je schaalmodel.

4: Hoeveel studenten kunnen er op het bankje staan voordat deze 10mm doorbuigt?

$$E = \frac{FL^3}{48I\delta}$$

5: Bedenk manieren waarop we het bankje minder door kunnen laten buigen bij hetzelfde aantal studenten (x).

6: Kunnen we het bankje beter breder of dikker maken?

https://eventrentall.nl/product/2x-bier-bankjes/

Uitleg E-modulus

De **elasticiteitsmodulus (E)** zegt hoe stijf een **materiaal** is.

Hoe hoger E, hoe minder het materiaal elastisch vervormt bij een bepaalde kracht.

Bijvoorbeeld: staal heeft een veel hogere E dan hout of kunststof, dus het rekt of buigt minder mee.

*E is een **materiaaleigenschap**: het verandert niet als je de vorm aanpast.*

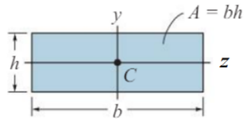
Material	Type	Young's Modulus (MPa)
Steel (mild)	Metal	200000–210000
Aluminum	Metal	69000–72000
Copper	Metal	110000–130000
Titanium	Metal	100000–120000
Brass	Metal	90000–110000
Polyethylene (HDPE)	Polymer	700–1400
Polypropylene	Polymer	1000–1800
Polystyrene (PS)	Polymer	3000–3500
PVC (rigid)	Polymer	2000–3500
Nylon (PA 6)	Polymer	2000–3500
Polycarbonate (PC)	Polymer	2000–2400
Epoxy (thermoset)	Polymer	2000–5000

Uitleg Traagheidsmoment

Het **traagheidsmoment (I)** geeft aan hoe stijf een **doorsnedevorm** is tegen buiging.

Hoe meer materiaal er verder van het midden (de buigas) ligt, hoe groter I, en hoe minder de balk buigt.

I hangt dus af van de **vorm en afmetingen** van de balk, vooral de hoogte:



$$I_z = \frac{1}{12}bh^3$$

*I is **géén materiaaleigenschap**, het verandert als je de vorm verandert.*

https://eventrentall.nl/product/2x-bier-bankjes/

Oktoberfest Bankje

14:59

Bij vraag 4 zijn we erachter gekomen dat er ongeveer x studenten op het bankje kunnen staan voordat deze 10mm doorbuigt.

7: Denk je dat we het bankje beter 50% breder of dikker kunnen maken? Reken uit wat het effect van beiden (apart) is op de doorbuiging.

8: Als we in plaats daarvan het materiaal veranderen naar Aluminium, hoeveer buigt het bankje dan door?

Material	Type	Young's Modulus (MPa)
Steel (mild)	Metal	200000–210000
Aluminum	Metal	69000–72000
Copper	Metal	110000–130000
Titanium	Metal	100000–120000
Brass	Metal	90000–110000
Polyethylene (HDPE)	Polymer	700–1400
Polypropylene	Polymer	1000–1800
Polystyrene (PS)	Polymer	3000–3500
PVC (rigid)	Polymer	2000–3500
Nylon (PA 6)	Polymer	2000–3500
Polycarbonate (PC)	Polymer	2000–2400
Epoxy (thermoset)	Polymer	2000–5000

https://eventrentall.nl/product/2x-bier-bankjes/

Oktoberfest Bankje

04:59

8: Wat kun jij als ontwerper beïnvloeden in dit soort situaties?

9: Welke inzichten kwamen pas ná het meten?

10: Welke inzichten kwamen pas ná het meten?

Appendix H3 Workshop Observations

H3.1 Workshop 1 - Intuitive

Group A
Group size: 1

Phase 1 – Intuitive sorting
- The student began by sorting based on visible characteristics and tactile feel (e.g. weight, texture, surface finish).
- Made an initial distinction between wood, plastic, and metal, but struggled to go further within those categories.
- Expressed uncertainty out loud: "This feels like metal but it's too light… maybe plastic?"
- Attempted to identify materials by analogy to known products: e.g. "This reminds me of a cutting board."

Phase 2 – Testing phase (after introduction of simple tools)
- Magnet test: used first, with quick and confident sorting between magnetic and non-magnetic samples.
- Scratch test: performed systematically, but interpretation varied. The student noted differences in scratch resistance but wasn't always sure how to interpret them.
- Conductivity test: initially uncertain, then used presence/absence of LED signal to sort into "probably metal" and "not metal."
- Thermal test: the student used touch to assess thermal conductivity. Said: "This one feels colder, so I guess it's a metal?", acknowledged this might be subjective.

Phase 3 – Density test
- Student showed visible relief at having a measurable method: "Finally something that gives an actual number."
- Measured mass and water displacement carefully and used the results to update previous guesses.
- Noted sources of inaccuracy, like absorbed water in porous materials, and questioned some results: "This can't be right… I must've measured the volume wrong."

Observed reasoning shift
- Clear shift from guessing to structured analysis during the workshop.
- Increasing reliance on measurable and testable properties rather than intuition alone.
- The density test served as a turning point: from hesitant classification to more confident, evidence-based reasoning.
- Student reflected on their earlier assumptions and revised them after each test.

Group B
Group size: 2

Phase 1 – Intuitive sorting
- The students began by comparing the materials visually and by touch. One focused mostly on surface texture and shine: "These definitely look like metal."
- The other was more cautious, testing weight by bouncing samples in their hands and saying: "This one's light, but still feels kind of hard."
- They sorted materials into general groups: "metal," "wood," and "plastic," though there was uncertainty around a few edge cases. One sample led to back-and-forth: "Could be plastic," "But look at the finis. maybe coated metal?"
- They mostly relied on prior experience, guessing based on what the material felt like from products they'd seen before. No written rationale yet.

Phase 2 – Testing phase (after introduction of simple tools)
Magnet test: Used immediately and correctly. One student ran through all samples and quickly identified magnetic ones. The other asked: "Can stainless steel be non-magnetic?" and they briefly discussed exceptions.
Scratch test: Both tested each sample with a nail. One focused on comparing groove depth, the other commented on sound and texture: "This one almost flakes off. That's weird." They weren't always sure how to link scratch results to material types.
Conductivity test: One student held the crocodile clips while the other observed the LED. When one sample didn't light up, they redid the connection: "Wait, was that a bad contact or is it really not conducting?" After double-checking, they concluded it was non-conductive.
Thermal test: Used by touch alone at first. One student rubbed two samples between their palms and said: "This one feels colder, but only just." The other was sceptical: "That might just be because it's been sitting out longer."

Phase 3 – Density test
- The students split tasks: one took care of weighing, the other measured water displacement. They discussed each step together and noted values.
- There was some confusion with units: "So grams divided by cubic centimetres, right?" but they figured it out quickly.
- When results didn't match their earlier guesses, they questioned possible causes: "Maybe some air got trapped?" They repeated one test to confirm.
- Initially, one student seemed less confident in the method, but became more comfortable as results matched expectations: "Okay, yeah, this lines up now."

Observed reasoning shift
- The group gradually moved from surface-based guessing to using test results as evidence.
- Differences in approach were visible: one student worked more decisively, the other was more reflective , they balanced each other well.
- They began to revise their initial groupings based on density and conductivity, rather than just look and feel.
- By the end, both students showed a stronger understanding of how different material properties relate to classification.

Group C
Group size: 2

Phase 1 – Intuitive sorting
- The group started without much discussion. One student (Student A) immediately began grouping materials by look and feel: "This one's definitely plastic," while the other (Student B) mostly watched and nodded.
- Student A tried to involve the other: "What do you think about this one?" but got a shrug in response: "Yeah, maybe."
- Some materials were sorted based purely on weight or colour. Student A said: "This feels heavy, so probably metal," without cross-checking with any other property.
- No clear reasoning was written down, and there was minimal collaboration. The group moved on quickly, despite obvious uncertainty.

Phase 2 – Testing phase (after introduction of simple tools)
Magnet test: Student A tested the materials while Student B stood back. When asked to help, B responded: "You're already doing it." One non-magnetic metal was incorrectly classified as plastic.
Scratch test: Student A applied the test to a few samples but skipped others. When one result was unclear, B suggested: "Maybe it's just worn-out plastic," with little explanation.
Conductivity test: The group appeared unsure about how to use the crocodile clips. They misconnected one test and concluded incorrectly that the material didn't conduct.
Thermal test: Barely used. Student A picked up a sample and said: "This one's cold, probably metal," but didn't compare with others. Student B responded: "They all feel the same to me."

Phase 3 – Density test
- Only three samples were tested before the group moved on. One measurement was skipped entirely after they misread the scale and gave up: "This is too fiddly."
- They didn't record volume properly and estimated values by sight. Student A: "Close enough, right?"
- When asked about discrepancies, B said: "I think the table is just off," rather than checking the method.
- The pair appeared rushed and didn't revisit earlier assumptions or adjust their initial classifications.

Observed reasoning shift
- Unlike other groups, this pair showed little development from intuition toward structured reasoning.
- Student A attempted to drive the process but grew visibly frustrated with the lack of participation: "You need to help me at least check stuff."
- Student B remained mostly disengaged, offering minimal input and deferring to A's decisions.
- Misclassifications were not corrected even after test results contradicted their guesses.
- Overall, the group missed several opportunities to use the tools to refine their understanding.

Appendix H3.2 Workshop 2: Structured

Group A
Group size: 1

Phase 1 – Initial estimation (no tools, no theory)
- The student began by thinking aloud: "Okay, I guess it depends on how thick the bench is, or how strong the wood is."
- Estimated that the bench could hold "maybe 4 or 5 students" before bending too far but wasn't sure what "too far" meant.
- Considered body weight briefly but didn't define a number: "Let's say like 70 kg per person?"
- Wrote down possible factors: material type, length of the bench, leg position, thickness. but admitted: "I don't know which matters most."

Phase 2 – Reflection (after initial reasoning)
- Said the estimate felt like "just a guess."
- Recognised missing data: "I'd want to know what kind of wood this is, or how stiff it is."
- Pointed out that it's unclear what counts as "too much bending," and wondered how that would be measured.
- Asked rhetorically: "Is there a way to calculate this, or do people just test it and see?"

Phase 3 – Access to scale model (experiment phase)
- Used the scale model to simulate loading by stacking weights.
- First tried rough loading: "Let's just see how far this goes before it looks bad."
- Measured deflection using a ruler and adjusted placement of weight to observe differences.
- Noted that the bending increased non-linearly: "It's bending way more between the second and third weight."
- Repeated the test and recorded deflection at different loads, then calculated the difference per added unit.

Phase 4 – Introduction of theory (after model use)
- After seeing the bending formula, immediately tried to match it to what was observed: "Okay, so force and span length matter a lot, L is to the third power?"
- Asked aloud: "Wait, so if I double the span, it bends eight times more?"
- Looked back at the scale model data and tried to plug values into the formula to test them.
- Correctly identified that material stiffness (E) and cross-section (I) are key, saying: "So if we can't change the material, we should make the bench thicker."

Observed reasoning shift
- Started with rough intuition but clearly moved toward structured reasoning based on observation and the provided formula.
- Treated the scale model as a tool for pattern recognition, not just trial and error.
- Used the formula to validate earlier observations rather than just plug in numbers.
- Demonstrated an understanding of both the role of geometry (I) and material (E) in stiffness by the end of the activity.

Group B
Group size: 2

Phase 1 – Initial estimation (no tools, no theory)
- The group began by discussing what might matter: "Probably the type of wood and how far the legs are apart," said Student A.
- Student B added: "Also the thickness , didn't we have something like this in mechanics class?"
- They assumed around 5–6 people could stand on the bench, based on "what it felt like at ID Kafe," but admitted it was just a rough guess.
- One student began sketching a side view of the bench and marked force points.

Phase 2 – Reflection
- They listed what they felt unsure about: the strength of the wood, how much bending was "too much," and whether bending would be the actual failure point.
- Student A: "I think I remember that deflection goes up with the cube of the length?"
- Student B: "Yeah, and material stiffness... what's it called again? E-something?"
- Both recognised the need for actual data, especially about the scale of acceptable bending.

Phase 3 – Access to scale model (experiment phase)
- They began by loading the scale model and noting down how far it bent under increasing weights.
- Tried using a calliper to measure deflection but struggled to keep it stable. Student B: "It's hard to measure the exact drop , it keeps sliding off."
- Switched to using a ruler pressed against the table edge for more consistent results.
- After leaving a weight on for a bit longer, Student A noted: "It keeps bending even when we don't touch it."
- Student B recognised it as creep: "That's creep, right? Slow deformation under load."
- They repeated the test quickly after removing the weight to see if it returned to shape, concluding it was still within the elastic range.

Phase 4 – Introduction of theory (after model use)
- Upon seeing the formula, Student B immediately recalled: "Yes, E is the stiffness, and I is the geometry."
- They linked the model results to the L^3 term: "No wonder small changes in span make a big difference."
- They tried back-calculating E from their measurements, with rough estimates of I.
- Student A joked: "We should've taken more accurate deflection values, now this is all fuzzy math."
- Still, they managed to explain how increasing thickness or reducing span would improve performance.

Observed reasoning shift
- The group transitioned from intuitive estimation to testing-based reasoning, and finally to theory-driven analysis.
- They balanced prior course knowledge with new observations from the model.
- Noticed secondary effects like creep on their own, without prompting.
- Tool handling (the calliper) introduced some uncertainty, which led to adaptation and reflection.
- By the end, they expressed a clear understanding of what parameters they could change as designers, and what was material-dependent.

Group C
Group size: 2

Phase 1 – Initial estimation (no tools, no theory)
- Student A immediately began estimating: "I don't know, maybe 4 or 5 people?" while Student B shrugged: "Sure, that sounds fine."
- Student A listed possible influencing factors (material, span, thickness), but didn't write anything down.
- Student B leaned back during the discussion and only occasionally responded. Student A: "Come on, just give me a number at least."
- No reasoning was used to support the estimate. They moved on quickly.

Phase 2 – Reflection
- Student A admitted they were "just guessing."
- B added: "I don't know how much bending is too much anyway," but didn't offer ideas on how to approach it.
- A said: "We need actual numbers or a test or something… we're just making stuff up right now."
- No mention of prior knowledge or mechanics theory.

Phase 3 – Access to scale model (experiment phase)
- Student A handled the model and placed weights. Student B observed but didn't assist unless prompted.
- They used a ruler to estimate deflection but took only one measurement per load.
- Student A grew frustrated after inconsistent readings: "You're not even looking, help me check if it's moving or not."
- B briefly joined in and commented: "It's kind of hard to tell where the lowest point is."
- They didn't notice the non-linear response or creep effects. The data wasn't recorded consistently.

Phase 4 – Introduction of theory (after model use)
- Student A looked at the formula and said: "Oh… so L^3. That's probably why it got bad fast."
- B asked: "What's this I thing again?" and A tried to explain: "Something about geometry… like shape resistance?"
- They looked back at their measurements and realised they should've taken more data. A: "We probably should've measured a few times and averaged it."
- B: "Yeah, but whatever. We got the general idea."
- They used the formula to plug in some rough estimates but didn't check accuracy or units.

Observed reasoning shift
- Limited development from intuition to structured reasoning.
- Student A tried to engage with the model and the theory, but lacked support from B, which affected depth of engagement.
- Reflection after theory revealed missed opportunities: they recognised better practices (like averaging measurements) only in hindsight.
- Some grasp of the formula's implications emerged, but without strong application.
- Overall, learning appeared more superficial compared to other groups.

Appendix I - Mechanical Validation

Appendix I1 - What are we measuring?

In this project, we calculate a material stiffness value based on force–deflection measurements obtained from a low-cost three-point bending setup. While this value is sometimes referred to as a "modulus," it does not correspond directly to the theoretical Young's modulus as defined in materials science.

Elastic Modulus vs Effective Modulus

The true elastic modulus (Young's modulus) is defined as the slope of the very first, perfectly linear segment of the stress–strain (or force–deflection) curve (Callister & Rethwisch, 2020; Beer et al., 2012). This region is extremely narrow, often within 0.1–0.5 mm of deflection in typical thermoplastics. Measuring this slope requires:

- high-resolution sensors,
- precise zeroing and tare capabilities,
- and a system free from mechanical play, friction, or early noise.

In our setup, like in other educational tools such as TU Delft's LED tensile tester — these conditions are not fully met. The early portion of the force–deflection curve is often distorted by mechanical slack, surface friction, or viscoelastic effects. As a result, the slope in the first 0.5 mm appears flatter than the true elastic behaviour of the material.

The Gradual Onset of Stiffness

This phenomenon is not only caused by measurement limitations, but also by material behaviour itself. Especially in viscoelastic materials, the internal molecular structure may allow initial deformation to occur with little resistance. Only after some alignment or stress redistribution does the material exhibit full elastic stiffness.
As explained in the Engineering LibreTexts resource on Linear Viscoelasticity:
"Linear viscoelastic materials will deform gradually under a constant load. The stress–strain curve shows an initial flattening, as internal molecular mechanisms absorb strain without much resistance, followed by a sharper elastic response as the structure aligns."
(Roylance, 2003)

Defining the Effective Modulus

To produce a usable and comparable stiffness value, we instead calculate an effective modulus. This is done by drawing a straight line between two clearly measurable points in the elastic region, typically at 1 mm and 2 mm of deflection.

This method is:
- more repeatable,
- less sensitive to friction or mechanical compliance,
- and more relevant for use in educational comparisons.

However, because this line is often steeper than the curve's earliest slope, the effective modulus can appear higher than the true elastic modulus. This does not mean the material is stiffer, it reflects both a delay in stiffness buildup and limitations in early measurement resolution.

Appendix I2 Deflection Measuring Accuracy

I.2.1 Introduction

This appendix documents a series of measurements aimed at evaluating the accuracy and consistency of displacement readings taken with a calliper in the three-point bending test setup. The deflection is measured directly between the indenter and the two anvil parts, explicitly isolating sample deformation and ignoring any effects from frame flex, load cell deformation, or support compliance.

Three aspects of the measurement were examined:
- Repeatability of calipee readings at a fixed position
- Systematic offsets from calliper placement (front/back, left/right)
- The influence of contact force used when placing the calliper

These effects were evaluated to understand and quantify the uncertainty in deflection measurements used for calculating E-modulus.

I.2.2 Test Setup

Three mechanical configurations of the setup were tested:
- S1: Indenter in high position, no load
- S2: Indenter in low position, no load
- S3: Indenter in low position, with sample loaded

At each configuration, calliper measurements were taken at four positions:
- Left side – back of flange
- Left side – front of flange
- Right side – back
- Right side – front

Each combination of situation and position was measured 10 times, attempting consistent technique and orientation.

Table I2.1 Raw Measurements in mm

Situation 1					Situation 2					Situation 3				
No.	Left-Back	Left-Front	Right-Back	Right-Front	No.	Left-Back	Left-Front	Right-Back	Right-Front	No.	Left-Back	Left-Front	Right-Back	Right-Front
1	22,61	22,6	22,43	22,46	1	19,62	19,61	19,44	19,45	1	18,1	18,09	17,92	17,91
2	22,61	22,59	22,42	22,44	2	19,58	19,56	19,42	19,43	2	18,12	18,11	17,94	17,93
3	22,66	22,65	22,45	22,45	3	19,6	19,59	19,43	19,44	3	18,09	18,08	17,91	17,9
4	22,65	22,64	22,44	22,45	4	19,61	19,6	19,41	19,42	4	18,11	18,1	17,93	17,92
5	22,62	22,63	22,41	22,43	5	19,59	19,58	19,4	19,41	5	18,1	18,09	17,9	17,89
6	22,67	22,66	22,46	22,47	6	19,6	19,6	19,45	19,45	6	18,11	18,1	17,93	17,92
7	22,64	22,63	22,42	22,44	7	19,57	19,55	19,39	19,4	7	18,08	18,07	17,89	17,88
8	22,57	22,56	22,4	22,42	8	19,63	19,62	19,42	19,43	8	18,13	18,12	17,95	17,94
9	22,63	22,61	22,43	22,46	9	19,58	19,57	19,4	19,41	9	18,09	18,08	17,9	17,89
10	22,59	22,6	22,42	22,45	10	19,59	19,59	19,43	19,44	10	18,1	18,09	17,92	17,91

H.2.3 Measurement Uncertainty

To evaluate repeatability, the standard deviation of repeated readings at each fixed position was calculated. Most values fell between 0.02 mm and 0.04 mm, with a maximum observed standard deviation of 0.045 mm (see Table I2.2). This variation represents the spread of readings due to user placement, alignment, and interpretation.

For this evaluation, digital callipers (Mitutoyo) were used with a resolution of 0.01 mm and accuracy of approximately ±0.02 mm (Mitutoyo, n.d.-a). However, during course use, students will use standard analogue callipers, which have a practical resolution and uncertainty of ±0.05 mm (Mitutoyo, n.d.-b). To determine a realistic overall measurement uncertainty for course conditions, both components, repeatability and resolution, were combined using the root-sum-of-squares (RSS) method (Joint Committee for Guides in Metrology, 2008).

$$Total\ Uncertainty = \sqrt{(0.03mm)^2 + (0.05mm)^2} \approx \pm 0.06\ mm$$

This ±0.06 mm value is used as the working uncertainty when evaluating how measurement error affects E-modulus calculations.

Table I2.2 Measurement Uncertainty

Position	Mean (mm)	Std Dev (mm)
Left-Back (S1)	22,628	0,031
Left-Front (S1)	22,607	0,03
Right-Back (S1)	22,428	0,02
Right-Front (S1)	22,447	0,018
Left-Back (S2)	19,599	0,02
Left-Front (S2)	19,587	0,023
Right-Back (S2)	19,419	0,02
Right-Front (S2)	19,424	0,017
Left-Back (S3)	18,103	0,016
Left-Front (S3)	18,093	0,016
Right-Back (S3)	17,919	0,019
Right-Front (S3)	17,91	0,018

I.2.4 Systematic Positional Offsets

Front vs. Back

Paired t-tests showed no statistically significant difference between front and back readings at either side (see Table I2.3). These positions may be used interchangeably as long as placement is consistent within a test.

Table I2.3 Positional Offsets Front vs Back

Side	Mean Front (mm)	Mean Back (mm)	Difference (mm)	p-value
Left (S1)	22,607	22,628	-0,021	0,43
Right (S1)	22,447	22,428	0,019	0,37
Left (S2)	19,587	19,599	-0,012	0,45
Right (S2)	19,424	19,419	0,005	0,67
Left (S3)	18,093	18,103	-0,01	0,52
Right (S3)	17,91	17,919	-0,009	0,58

Left vs. Right
Measurements on the left side consistently differed from those on the right. Mean offsets of up to 0.18 mm were observed, all with statistically significant p-values ($p < 0.05$, see Table H2.4). This suggests a structural bias, possibly due to slight frame asymmetries or part misalignment.

Table I2.4 Positional Offsets Left vs Right

Situation	Left Mean (mm)	Right Mean (mm)	Difference (mm)	p-value
S1	22,618	22,437	0,181	0,0001
S2	19,593	19,422	0,171	0,0003
S3	18,098	17,915	0,183	0,0001

This positional bias is not included in the general measurement uncertainty, since it is systematic, not random. Instead, it should be addressed by either:

- Always measuring from the same side, or
- Averaging left and right readings

I.2.5 Effect of Load on Measurement Variation

To see if mechanical load affects the stability of calliper readings, the standard deviations from the unloaded condition (S2) and loaded condition (S3) were compared for each side.
In both left and right cases, the variation remained constant or slightly decreased under load. This suggests that the interface between the calliper and the setup remains stable, even with sample force applied. Results are shown in Table I2.5.

Table I2.5 Influence of Load on Measurement

Side	SD Without Load (S2)	SD With Load (S3)	Change in SD	F-Statistic
Left	0,02	0,016	-0,004	1.56
Right	0,02	0,019	-0,001	1.11

I.2.6 Exploratory Test: Effect of Calliper Contact Force

A follow-up test was conducted to explore how user-applied contact force affects calliper readings. This test focused on a single position (Left-Back), previously shown to be stable.
Four combinations of force were tested:

- Firm on both indenter and anvil
- Firm on indenter, light on anvil
- Light on indenter, firm on anvil
- Light on both indenter and anvil

Each combination was measured 10 times. The full data is shown in Table I2.6.

The maximum difference between the mean values was 0.204 mm, which corresponds to a spread of approximately ±0.1 mm around the centre see Table I2.7 on the next page.

Table I2.6 Influence of Calliper Force Variation

Measurement No.	Firm/Firm	Firm/Light	Light/Firm	Light/Light
1	20,35	20,21	20,37	20,33
2	20,3	20,18	20,44	20,29
3	20,32	20,16	20,38	20,33
4	20,32	20,2	20,41	20,34
5	20,35	20,19	20,38	20,29
6	20,27	20,23	20,4	20,31
7	20,31	20,23	20,41	20,28
8	20,29	20,17	20,35	20,31
9	20,3	20,2	20,45	20,33
10	20,33	20,19	20,41	20,33

Table I2.7 Force combination outcomes

Force Combination	Mean (mm)	Std Dev (mm)
Firm/Firm	20,312	0,027
Firm/Light	20,196	0,025
Light/Firm	20,4	0,032
Light/Light	20,314	0,03

Although this variation is greater than the standard deviation seen in consistent measurements, it still falls close to the defined ±0.06 mm uncertainty band.

I.2.7 Conclusions

The deflection measurements using the calliper method showed consistent results across repeated trials. Most standard deviations stayed between 0.02 mm and 0.04 mm. When combined with the typical resolution of analogue callipers, a realistic total uncertainty of ±0.06 mm was established.

Left and right measurement positions showed systematic differences of up to 0.18 mm. These are not treated as random uncertainty but should be handled through consistent placement or by averaging both sides. No meaningful difference was found between front and back positions.

Applying load to the system had no measurable effect on measurement variation. The setup remained stable, even when a sample was in place. An additional test on contact force showed a possible influence of around ±0.1 mm depending on how the calliper was pressed, highlighting the need for consistent handling.

Appendix I.3 Weight Measuring Accuracy

I.3.1 Introduction

This appendix contains a short evaluation of the accuracy of the load cell used in the structured three-point bending test setup. The load cell had been previously calibrated using a set of known weights, with a linear scaling factor applied to convert raw amplifier output to grams. The aim of this evaluation was to check the accuracy of that calibration and determine the resulting uncertainty to be included in the calculation of the effective modulus.

Figure I1 Load Cell Test

I.3.2 Test Setup

The test was performed using the same mechanical test device as used during bending measurements. The setup was placed near the edge of a table, allowing weights to hang freely beneath the device (Figure I1)

A small custom bracket tool was used to apply the load to the indenter. This tool rests across the anvil supports and extends beyond the frame on both sides. A thin rope was attached to the ends of the bracket, forming a loop that hung below the setup. Weights were hung in this rope to apply a known vertical load to the centre of the device, directly through the load cell. The configuration ensures that the force is applied along the same axis as in actual bending tests.

I.3.3 Results

The table below shows the known weights and their corresponding measured values. A second reading was taken after 60 seconds to check for drift or instability. The table includes the difference between applied and measured values in both grams and percentage.

Table I3.1 Weight Results

Weight (g)	Weight Measured (g)	Weight after 60s (g)	Difference (g)	Difference (%)
461	459	459	-2	-0,43
1198	1193	1193	-5	-0,42
1503	1501	1501	-2	-0,13
2309	2320	2320	11	0,48
2997	3009	3009	12	0,40
3856	3858	3858	2	0,05
4291	4291	4291	0	0,00
4657	4687	4687	30	0,64
5123	5149	5149	26	0,51
5897	5925	5925	28	0,47
6778	6806	6806	28	0,41
7516	7544	7544	28	0,37
9728	**9758**	**9758**	30	0,31

- Maximum deviation: 30 g (0.64%)
- Typical deviation: 0.3–0.5%
- No observed drift between initial and 60-second readings

I.3.4 Discussion

The observed deviations were small and consistent, suggesting that the load cell is well-calibrated for the range of forces expected in this setup. The largest error (0.64%) occurred at mid-range loading and may reflect slight variation in how the weight was applied. Since no trend of increasing error with weight was observed, a flat ±0.5% uncertainty is appropriate.

During testing, the HX711 occasionally produced single-readout spikes of up to 3000 grams. These only lasted for one measurement cycle and immediately returned to normal values. The issue appeared randomly. The spikes were more frequent when powering the system via certain laptop USB ports or phone charging bricks. Using a more stable power supply noticeably reduced the effect. Based on this, it was concluded that the spikes were most likely caused by an unstable or noisy power source, which is a known issue with the HX711 without proper filtering or grounding.

Since the spikes were easy to recognise, they could be ignored while writing down data during tests and didn't affect the final results. Still, adding power filtering (e.g. bypass capacitors) or switching to a regulated power supply is recommended for future use.

I.3.5 Conclusion

The test confirms that the load cell gives reliable readings within the tested range. The deviations stayed within acceptable limits, and no drift was observed. This supports the calibration that was previously applied and provides a realistic estimate of the measurement uncertainty. A relative uncertainty of ±0.5% will be used in further calculations of the effective modulus.

Appendix I4 Effect of Measuring Accuracy on Effective Modulus

I4.1 Introduction

This section combines the measurement uncertainties from previous appendices and looks at how they affect the calculation of the effective modulus. The modulus is based on the slope between two points on the force–deflection curve. To get to a final value, deflection, force, and sample geometry all play a role.

I.4.2 Deflection Uncertainty

As explained in Appendix I2, deflection was measured using callipers with a typical uncertainty of ±0.06 mm. The modulus is calculated using two points (1 mm and 2 mm of deflection) so the uncertainty applies to both measurements. When combined, the uncertainty in the difference between the two points (Δd) comes out to 0.085 mm, using the RSS method (Joint Committee for Guides in Metrology, 2008).

This leads to a relative error of 8.5% in the deflection term alone. Since the modulus is calculated from the force-over-deflection slope, this error has a direct effect on the result.

I.4.3 Force Measurement Uncertainty

The force was measured using a load cell, which was evaluated in Appendix I3. The differences between real and measured weights were consistent and small. The largest error was 0.64%, but most values stayed between 0.3% and 0.5%. A relative uncertainty of ±0.5% was considered a safe, conservative estimate to carry forward in the modulus calculations.

I.4.4 Sample Geometry Uncertainty

The moment of inertia, used in the modulus formula, depends on the sample's width and height. The height especially matters because it's raised to the power of three in the formula:

$$E = \frac{wh^3}{12}$$

So, since uncertainty in height quickly has a bigger effect. The height and width were both measured with analogue callipers with a resolution of ±0.05 mm.

For a typical sample of 15.00 mm width and 2.00 mm height, the moment of inertia is:

$$I = \frac{15 \cdot 2^3}{12} = 10.00mm^4$$

To estimate the uncertainty, we multiply the sensitivity of the formula to each variable with its uncertainty:

The width contributes:

$$\left(\frac{h^3}{12}\right) \cdot 0.05 = \left(\frac{8}{12}\right) \cdot\ 0.05 = 0.67 \cdot 0.05 = 0.33mm^4$$

The height contributes:

$$\left(\frac{w \cdot h^2}{12}\right) \cdot 0.05 = \left(\frac{15 \cdot 4}{12}\right) \cdot\ 0.05 = 15 \cdot 0.05 = 0.75mm^4$$

These two contributions are combined using RSS:

$$\Delta I = \sqrt{0.033^2 + 0.75^2} \approx 0.75\ mm^4$$

Relative uncertainty in I:

$$\frac{0.75}{10.00} \times 100\% = 7.5\%$$

This 7.5% uncertainty in the moment of inertia is therefore included in the total uncertainty on the effective modulus.

I.4.5 Combined Uncertainty

The effective modulus is calculated as:

$$E = \frac{\Delta F L^3}{4 w h^3 \Delta d}$$

The uncertainty in E depends on uncertainties in the measured force difference (ΔF), the deflection difference (Δd), and the sample geometry (through the moment of inertia).

$$\frac{0.75}{10.00} \times 100\% = 7.5\%$$

The relative uncertainties are:

- Deflection difference: ±8.5%
- Force difference: ±0.5%
- Moment of inertia (geometry): ±7.5%

Using the RSS Method again, the total relative uncertainty in the effective modulus is:

$$\sqrt{8.5^2 + 0.5^2 + 7.5^2} \approx 11.3\%$$

This shows that deflection and geometry uncertainties dominate the overall error, while force measurement uncertainty contributes minimally.

I.4.6 Conclusion

The combined measurement uncertainties lead to an estimated total relative uncertainty of about ±11.3% in the effective modulus. This means that all stiffness values calculated in this project carry this level of uncertainty.

While the deflection measurement is the main contributor, the geometric measurement of sample height (due to it's to the power of three) also significantly affects the results. Force measurement uncertainty is comparatively small.

For the purposes of this project, which focuses on educational and comparative material testing, this uncertainty level is acceptable. It sets a realistic expectation for the accuracy of the effective modulus values and underlines the importance of consistent measurement technique and careful sample preparation.
This understanding helps interpret the results appropriately and supports the validity of conclusions drawn from the stiffness comparisons made using the developed test setup.

Appendix I.5 Vernier Scale

I.5.1 Introduction

The vertical displacement of the indenter in the test device is controlled by a screw-driven knob with an attached vernier scale. Each full rotation of the M8 screw advances the indenter by 1.25 mm, and the scale is divided into 25 steps, nominally 0.05 mm per step. This test evaluates whether the indicated displacement matches the actual movement of the indenter.

I.5.2 Testing Method

The knob was rotated in 0.25 mm increments according to the vernier scale, and the vertical position of the indenter was measured using a digital calliper. Two datasets were collected:

- Test 1: One single-pass measurement.
- Test 3: One set of three measurements per step, averaged to reduce noise.

Measurements were taken over a 4.5 mm range.

I.5.3 Results

Table I5.1 Nonius 1

Nonius [mm]	M [mm]	Per step	Diff from Vernier
0,00	22,97		
0,25	22,81	0,16	-0,09
0,50	22,54	0,27	0,02
0,75	22,25	0,29	0,04
1,00	21,98	0,27	0,02
1,25	21,80	0,18	-0,07
1,50	21,57	0,23	-0,02
1,75	21,27	0,30	0,05
2,00	20,98	0,29	0,04
2,25	20,74	0,24	-0,01
2,50	20,54	0,20	-0,05
2,75	20,27	0,27	0,02
3,00	20,07	0,20	-0,05
3,25	19,75	0,32	0,07
3,50	19,40	0,35	0,10
3,75	19,22	0,18	-0,07
4,00	19,07	0,15	-0,10
4,25	18,93	0,14	-0,11
4,50	18,70	0,23	-0,02

Table I5.2 Nonius 2

Nonius [mm]	M1 [mm]	M2 [mm]	M3 [mm]	Avg M	Per Step	Diff from nonius
0,00	21,34	21,44	21,42	21,40		
0,25	21,14	21,09	21,10	21,11	0,29	0,04
0,50	20,88	20,80	20,84	20,84	0,27	0,02
0,75	20,56	20,60	20,55	20,57	0,27	0,02
1,00	20,30	20,30	20,33	20,31	0,26	0,01
1,25	20,05	20,09	20,08	20,07	0,24	-0,01
1,50	19,80	19,87	19,82	19,83	0,24	-0,01
1,75	19,54	19,56	19,59	19,56	0,27	0,02
2,00	19,27	19,31	19,33	19,30	0,26	0,01
2,25	19,09	19,09	19,09	19,09	0,21	-0,04
2,50	18,89	18,92	18,94	18,92	0,17	-0,08
2,75	18,67	18,65	18,67	18,66	0,25	0,00
3,00	18,44	18,37	18,39	18,40	0,26	0,01
3,25	18,04	18,11	18,00	18,05	0,35	0,10
3,50	17,77	17,87	17,81	17,82	0,23	-0,02
3,75	17,64	17,56	17,59	17,60	0,22	-0,03
4,00	17,32	17,30	17,29	17,30	0,29	0,04
4,25	17,03	17,10	17,14	17,09	0,21	-0,04
4,50	16,89	16,87	16,79	16,85	0,24	-0,01

In the averaged dataset, per-step displacement varied between 0.17 mm and 0.35 mm. Most steps fell between 0.24 mm and 0.27 mm, close to the expected 0.25 mm. Deviations from the vernier-indicated position were typically within ±0.05 mm, with occasional outliers up to ±0.10 mm.

Table I5.3 Average and Standard Deviation

Test1	Avg step	Stdev
1	0,24	0,06
2	0,25	0,04

I.5.4 Discussion

The results confirm that the vernier scale provides reasonably accurate control of indenter displacement over the tested range. Small variations per step are likely due to mechanical play, user input variability, or tolerances in the screw mechanism. No major hysteresis or backlash was observed.

I.5.5 Conclusion

The vernier scale is suitable for coarse positioning of the indenter. However, due to variability in actual displacement, it is not accurate enough for direct measurement of sample deflection. All critical measurements should continue to rely on direct instrumentation (e.g. callipers or sensors). Since this part is not used for actual measurements, it has no effect on the resulting Effective Modulus.

Appendix I.6 Load Cell Deflection

I.6.1 Introduction

This test was carried out to measure mechanical deflection in the load cell assembly. The main goal was to determine how much of the applied force results in internal movement.

I.6.2 Testing Method

The indenter was used to apply force directly onto a rigid U-shaped steel block placed on the anvil. No sample was involved, the setup created a closed loop through the frame, load cell, and indenter.
A digital calliper was mounted to the device. Its protruding back plate rested against the lower surface of the measuring flange. while the measuring tip contacted the top of the anvil. This captured the vertical distance between the main frame and the anvil (i.e. the load cell body). As a result, any compression in the load cell or flex in the frame was included in the reading.

I.6.3 Results

Deflection increased from 0.28 mm to 0.92 mm across a load range of 2.6 kg to 9.7 kg. The effective stiffness, calculated as deflection per unit mass. stayed between 0.09 and 0.11 mm/kg. The trend was largely linear.

Table I6.1 Load Cell Deflection Results

Force (g)	Deflection (mm)	F (kg)	Δd	mm/kg
6	24,94			
2579	25,22	2,579	0,28	0,11
6227	25,56	6,227	0,62	0,10
7907	25,62	7,907	0,68	0,09
9002	25,75	9,002	0,81	0,09
9657	25,86	9,657	0,92	0,10

I.6.4 Discussion

The system shows consistent mechanical behaviour within the tested range. However, it's clear the deflection isn't just from the load cell. Since the measurement was taken from the frame to the anvil, any frame deformation is also included.

In fact, the structure has failed. The load cell is visibly tilted in its housing, and the anvil part no longer sits level. That confirms part of the displacement is due to permanent deformation, not just elastic movement.

The measured stiffness (0.10 mm/kg on average) therefore overestimates true load cell compression. It's a combined result of cell compression plus frame compliance and likely some plastic deformation as well.

I.6.5 Conclusion

The system shows a linear response between 2.5 and 9.5 kg, with a typical stiffness of ~0.10 mm/kg. But this includes structural deflection. Without correction, displacement readings will not accurately reflect sample behaviour. Frame reinforcement or an isolated measurement method is needed before relying on this setup for precise testing.

Appendix I7 - Device Validation via Sample Testing

I.7.1 Overview

This appendix presents the results of a precision comparison between the student-built material testing device and the Low-End Tensile Tester (LETT) used at TU Delft. This comparison was developed as part of the broader analysis of bending test results and emerged from efforts to understand the repeatability of the student device across different materials.

The aim was not to determine how accurate the device is compared to standardized lab equipment, but rather to assess how consistent the results are when the same type of material is tested multiple times. For educational use, this kind of repeatability is far more valuable than absolute accuracy, students need results they can trust and reproduce, not necessarily values that match industry databases.

I.7.2 Test Setup

Four materials were tested:

- PMMA
- PETG
- PVC
- PS

Each material was tested on two setups:

- The student-built device, operated manually
- The LETT system, which applies load digitally and uses curve fitting

Each setup tested 3 strips per material, with 2 tests per strip:

- 6 measurements per material per device
- 24 measurements per device
- 48 total measurements

The student device uses a calliper to measure deflection between the anvil and indenter. While this excludes frame or load cell deflection from the reading, the load cell itself does bend under load (Appendix I.6) The deflection values (1 and 2mm) are targeted using the vernier scale, this vernier scale (Appendix I.5) does not take the Load Cell deflection into account, because of this actual sample deflections were likely closer to 0.80 mm and 1.70 mm.

Aluminium was originally included in the material set but was excluded after it showed clear signs of plastic deformation even at small deflections. This resulted in inconsistent stiffness measurements and confirmed that the material was not suitable for this test setup.

I.7.3 Results

The precision of each setup was evaluated using four metrics:

- Mean absolute deviation from the material's own average [MPa]
- Mean percentage deviation from the material's own average
- Standard deviation of Young's modulus [MPa]
- Standard deviation (%)

Each metric reflects how tightly grouped the results were for repeated tests on the same material. This approach focuses entirely on repeatability, independent of how close the values are to textbook definitions.

Table I7.1 Device to LETT Comparison results overview

	ABS Dis. Avg.	% Dis. Avg.	St. Dev [MPa]	St. Dev (%)
Device	110,15	4,78	135,98	6,03
LETT	193,40	7,25	253,01	9,57

The student device outperformed the LETT in all four measures, showing more stable results when the same material was tested repeatedly.

To explore the differences further, standard deviation was also calculated for each material separately, as shown in Table I7.2.

Table I7.2 Material Comparison

	PMMA	PETG	PVC	PS
Stdev (%) Device	6,62	3,71	3,14	10,21
Stdev (%) LETT	10,57	7,95	2,38	15,66

The full dataset used to produce these results is included in Appendix I.7.6.

I.7.4 Discussion

The results show that the student device produced more repeatable measurements than the LETT in 3 out of 4 materials. While this might be surprising at first, given the LETT's digital sensors and curve fitting, the reasons become clearer on closer inspection.

The student device measures stiffness at two manually selected force–deflection points. This approach keeps the test within the elastic region of most polymers and avoids noise from post-yield behaviour. While the LETT does not measure at the same force-deflection points even though it is aiming for it, which can cause more noise. Additionally, the LETT overshoots its aiming point of 2mm deflection, this could cause the sample to plastically deform which can influence the results of the second measurement of the same sample

.
The variation between materials also supports this explanation. PS, a brittle material, showed the highest variation in both setups. Its sensitivity to alignment, cracking, or surface flaws makes it harder to test consistently. PVC and PETG, on the other hand, were much more consistent, likely due to their ductility and predictable deformation.

In general, the results suggest that:
- Materials that require lower force to reach target deflection tend to show higher percentage variation, since small force errors represent a larger portion of the total.
- The student device is more stable when used within a controlled deflection range, especially with ductile materials.
- Even though the LETT is more advanced, its broader curve method introduces extra sources of variation.

I.7.5 Conclusion

Despite its simple design, the student-built test device demonstrated strong repeatability in Young's modulus measurements. The data shows clearly that it produced more consistent results than the LETT in most cases, especially when used with care and within appropriate deflection limits. This makes it highly suitable for the educational setting it is meant for.

I.7.6 Raw Data

Table I7.3 Device Results

Material	ID	v	δ1[mm]	δ2 [mm]	F1 [g]	F2 (g)	Δδ [mm]	ΔF (g)	E Modulus [Gpa]	E Modulus [MPa]	Span Length [mm]
PMMA	1	a	18,85	18,00	1680	3440	0,85	1760	2,97	2971,58	40,00
		b	18,80	18,00	1668	3550	0,80	1882	3,38	3376,16	40,00
PMMA	2	a	19,15	18,35	1886	3760	0,80	1874	3,32	3324,13	40,00
		b	19,20	18,45	1950	3823	0,75	1873	3,54	3543,85	40,00
PMMA	3	a	18,90	18,15	1611	3330	0,75	1719	3,18	3183,69	40,00
		b	18,90	18,10	1637	3430	0,80	1793	3,11	3113,19	40,00
PETG	1	a	18,85	18,00	1150	2430	0,85	1280	1,87	1873,66	40,00
		b	18,90	18,00	1197	2480	0,90	1283	1,77	1773,71	40,00
PETG	2	a	18,90	18,05	1201	2501	0,85	1300	1,90	1896,65	40,00
		b	18,95	18,05	1180	2445	0,90	1265	1,74	1743,05	40,00
PETG	3	a	19,05	18,20	1060	2343	0,85	1283	1,91	1907,35	40,00
		b	18,90	18,00	1160	2490	0,90	1330	1,87	1867,37	40,00
PVC	4	a	19,30	18,55	2151	4599	0,75	2448	2,97	2974,71	40,00
		b	19,30	18,60	2129	4561	0,70	2432	3,17	3166,36	40,00
PVC	5	a	19,35	18,60	2083	4475	0,75	2392	2,98	2983,22	40,00
		b	19,30	18,55	2223	4680	0,75	2457	3,06	3064,28	40,00
PVC	6	a	19,30	18,60	2283	4724	0,70	2441	3,12	3119,54	40,00
		b	19,30	18,60	2219	4733	0,70	2514	3,21	3212,83	40,00
PS	1	a	19,00	18,10	1235	2450	0,90	1215	1,70	1699,14	40,00
		b	18,95	18,00	1093	2280	0,95	1187	1,57	1572,62	40,00
PS	2	a	18,90	18,10	1187	2407	0,80	1220	1,90	1898,70	40,00
		b	19,05	18,10	1233	2411	0,95	1178	1,54	1543,86	40,00
PS	3	a	19,00	18,00	1229	2421	1,00	1192	1,49	1485,09	40,00
		b	18,95	18,10	1240	2505	0,85	1265	1,85	1854,16	40,00

Table I7.4 LETT Results

Material	ID	v	δ1[mm]	δ2 [mm]	F1 [N]	F2 (N)	Δδ [mm]	ΔF (N)	E Modulus [Gpa]	E Modulus [MPa]	L [mm]	I
PMMA	4	a	0,86	1,97	15,42	45,92	1,11	30,50	3,90	3895,94	40	9,40
		b	1,15	2,14	18,53	49,43	0,99	30,90	4,43	4425,46	40	9,40
PMMA	5	a	0,87	1,82	19,08	48,27	0,95	29,19	3,41	3405,54	40	12,03
		b	0,87	1,96	12,73	47,50	1,09	34,77	3,54	3535,53	40	12,03
PMMA	6	a	0,96	1,98	20,32	48,85	1,02	28,53	4,11	4111,42	40	9,07
		b	1,17	2,15	24,15	51,40	0,98	27,25	4,28	4281,84	40	8,66
PETG	4	a	0,89	1,86	11,29	30,33	0,97	19,04	2,45	2446,66	40	10,70
		b	0,90	1,87	13,26	29,96	0,97	16,70	2,15	2145,96	40	10,70
PETG	5	a	0,98	1,93	13,19	32,14	0,95	18,95	2,45	2451,77	40	10,85
		b	1,04	2,00	16,21	32,75	0,96	16,54	2,12	2117,67	40	10,85
PETG	6	a	0,98	1,95	13,82	30,18	0,97	16,36	2,05	2049,77	40	10,97
		b	0,77	2,14	7,58	31,68	1,37	24,10	2,14	2137,91	40	10,97
PVC	1	a	1,07	1,96	39,22	74,70	0,89	35,48	3,89	3886,31	40	13,68
		b	0,85	2,19	17,73	73,87	1,34	56,14	4,08	4084,24	40	13,68
PVC	2	a	1,18	2,06	33,16	67,48	0,88	34,32	3,86	3856,61	40	13,48
		b	0,87	1,87	26,48	66,07	1,00	39,59	3,91	3914,96	40	13,48
PVC	3	a	0,82	1,88	21,81	65,57	1,06	43,76	3,90	3902,34	40	14,11
		b	0,76	1,86	15,72	60,10	1,10	44,38	3,81	3813,71	40	14,11
PS	4	a	1,04	2,20	12,22	26,99	1,16	14,77	1,62	1616,00	40	10,51
		b	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	40	10,51
PS	5	a	0,92	1,93	6,40	23,37	1,01	16,97	2,17	2168,60	40	10,33
		b	1,08	2,01	10,18	22,92	0,93	12,74	1,77	1768,09	40	10,33
PS	6	a	0,90	1,81	5,45	21,91	0,91	16,46	2,32	2319,15	40	10,40
		b	0,95	1,93	10,91	23,09	0,98	12,18	1,59	1593,53	40	10,40

I	w [mm]	h [mm]	Mat. Average	Dis. fr. Avrg.	% diff.
9,11	14,75	1,95	3252,10	-280,52	-8,63
9,11	14,75	1,95	3252,10	124,06	3,81
9,22	14,69	1,96	3252,10	72,03	2,22
9,22	14,69	1,96	3252,10	291,75	8,97
9,42	14,78	1,97	3252,10	-68,41	-2,10
9,42	14,78	1,97	3252,10	-138,91	-4,27
0,51	15,08	2,03	1843,63	30,03	1,63
0,51	15,08	2,03	1843,63	-69,92	-3,79
0,55	15,13	2,03	1843,63	53,02	2,88
0,55	15,13	2,03	1843,63	-100,58	-5,46
0,35	15,07	2,02	1843,63	63,71	3,46
0,35	15,07	2,02	1843,63	23,74	1,29
4,35	14,92	2,26	3086,82	-112,11	-3,63
4,35	14,92	2,26	3086,82	79,54	2,58
3,98	14,93	2,24	3086,82	-103,60	-3,36
3,98	14,93	2,24	3086,82	-22,54	-0,73
4,62	15,00	2,27	3086,82	32,71	1,06
4,62	15,00	2,27	3086,82	126,00	4,08
0,39	15,13	2,02	1675,60	23,55	1,41
0,39	15,13	2,02	1675,60	-102,98	-6,15
0,51	15,07	2,03	1675,60	223,11	13,32
0,51	15,07	2,03	1675,60	-131,73	-7,86
0,50	15,06	2,03	1675,60	-190,51	-11,37
0,50	15,06	2,03	1675,60	178,56	10,66

w [mm]	h [mm]	Mat. Average	Dis. fr. Avrg.	% diff.
14,76	1,97	3942,62	-46,68	-1,18
14,76	1,97	3942,62	482,84	12,25
14,73	2,14	3942,62	-537,08	-13,62
14,73	2,14	3942,62	-407,09	-10,33
14,68	1,95	3942,62	168,80	4,28
14,68	1,92	3942,62	339,22	8,60
15,12	2,04	2224,96	221,70	9,96
15,12	2,04	2224,96	-78,99	-3,55
15,11	2,05	2224,96	226,81	10,19
15,11	2,05	2224,96	-107,29	-4,82
15,06	2,06	2224,96	-175,19	-7,87
15,06	2,06	2224,96	-87,04	-3,91
14,80	2,23	3909,70	-23,39	-0,60
14,80	2,23	3909,70	174,54	4,46
14,99	2,21	3909,70	-53,08	-1,36
14,99	2,21	3909,70	5,26	0,13
14,86	2,25	3909,70	-7,36	-0,19
14,86	2,25	3909,70	-95,98	-2,45
15,07	2,03	1893,07	-277,07	-14,64
15,07	2,03			
15,04	2,02	1893,07	275,52	14,55
15,04	2,02	1893,07	-124,98	-6,60
15,14	2,02	1893,07	426,07	22,51
15,14	2,02	1893,07	-299,54	-15,82

A hands-on, two-stage material-testing setup that bridges theory and practice in TU Delft's UPE course. The "Determination Station" combines intuitive sensory tools with a compact three-point–bend device (laser-cut, 3D-printed, €43/ complete setup) to let students explore hardness, density and stiffness, then measure force/deflection to calculate an effective modulus. Tested in workshops, it boosted understanding, confidence, and engagement while fitting UPE's Productive Failure model.