

Designing a Tangible Conceptual Learning Tool for Mechanical Understanding



Mechanical Garden

IPD Master Thesis

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July 2026

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MSc Thesis
Industrial Design Engineering
Delft University of Technology

Designing a tangible learning tool for mechanical understanding

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AI Disclosure

Artificial Intelligence (AI) tools were used during the development of this thesis to support writing and programming activities. Specifically, ChatGPT and Notebook LM were used to assist with language refinement, text editing, and programming-related tasks. All generated output was reviewed and adapted by the author before inclusion in the thesis.

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The author remains fully responsible for the content, accuracy, interpretations, design decisions, and conclusions presented in this thesis.

Acknowledgements

This project marks the completion of my Master’s in Industrial Design Engineering at TU Delft. It allowed me to follow my passion for making and prototyping while creating a learning tool that I hope will help future students beginning the same educational journey that I once started.

This project would not have been possible without the kind, knowledgeable, and supportive people who contributed to it.

First, I would like to sincerely thank my graduation mentors, Aadjan van der Helm and Bas Flipsen. They guided and supported me throughout this project, provided valuable feedback and knowledge, and were always willing to listen whenever new challenges or obstacles arose. Their enthusiasm and confidence in the project encouraged me to keep improving the Mechanical Garden and helped shape it into what it has become.

Secondly, I would like to thank all the educators from the Faculty of Industrial Design Engineering at TU Delft who took the time to participate in interviews, provide feedback on prototypes, and discuss new ideas and potential applications. Specifically Freerk Wilbers, Pien Jager, Stefan Persaud, Ernest van Breemen, Jordan Boyle, Senthil Chandrasegaran. Their knowledge and insights helped create a project that has the potential to become a valuable addition to the curriculum.

I would also like to thank all the students who participated in the evaluation of the Mechanical Garden. Their enthusiasm, feedback, and willingness to experiment with the system provided valuable insights that contributed to the further development of the project.

Thirdly, I would like to thank my family for their unconditional love and support throughout this project. Their encouragement helped me through the more difficult moments and motivated me to keep moving forward.

Finally, I would like to thank my partner, Naomi, for always being there to listen, providing thoughtful feedback, and giving me endless love and support throughout this journey.

This project would not have been possible without all of these talented, knowledgeable, supportive, and caring people.

Thank you all.

Summary

Designing a Tangible Conceptual Learning Tool for Mechanical Understanding

Industrial Design Engineering students frequently encounter difficulties applying mechanical principles during the design and prototyping process. While theoretical knowledge is provided throughout the curriculum, observations made during three years as a teaching assistant, supported by educator interviews and literature, showed that many students struggle to translate intended movement into technically feasible mechanisms. Students often rely on trial-and-error, have limited opportunities for hands-on experimentation, and spend valuable project time constructing prototypes instead of exploring mechanical concepts.

This graduation project investigated how a tangible learning tool could support students in moving from abstract theoretical knowledge towards a more

intuitive understanding of mechanical principles.

Using a Research-through-Design approach, the project combined literature research, observations, educator interviews, iterative prototyping, and user evaluations to develop and refine a new educational product.

Throughout the project, five exploratory prototypes were created to investigate different educational approaches, interaction methods, and construction systems. Insights from these iterations were gradually combined into the Mechanical Garden, a modular learning platform designed specifically for Industrial Design Engineering students. The system allows users to rapidly build, modify, and experiment with mechanisms

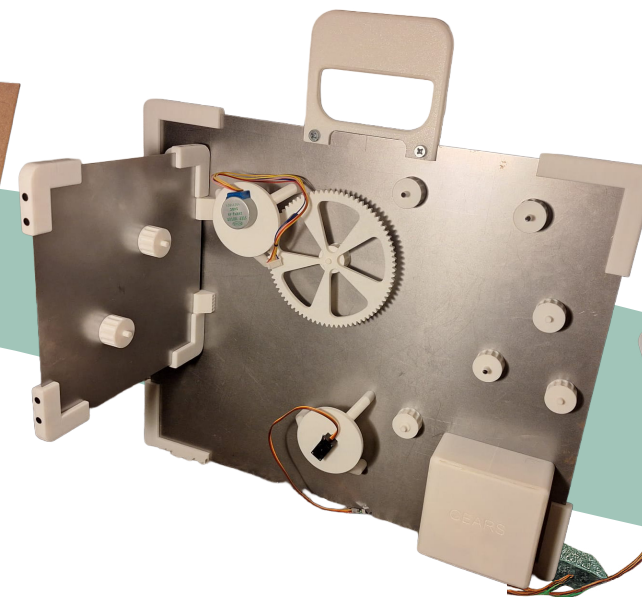
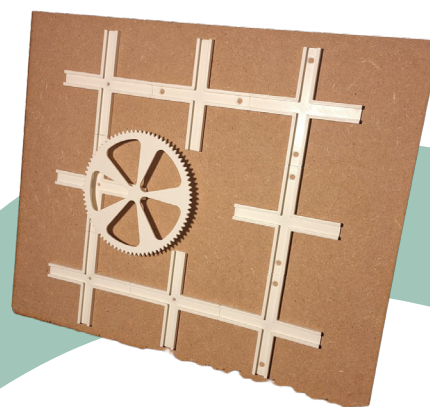
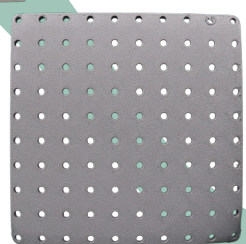
such as gears, four-bar linkages, and rack-and-pinion systems while immediately observing the consequences of their design decisions. The learning platform is complemented by educational support material and exercises that encourage active experimentation instead of passive observation.

The Mechanical Garden was evaluated with seven participants using pre-tests, post-tests, questionnaires, observations, and interviews. Results demonstrated substantial improvements in conceptual understanding. Average test scores increased from 54% before using the system to 91% afterwards, while participants consistently reported that the physical interaction made mechanical concepts easier to understand, encouraged experimentation, and helped

them relate theoretical knowledge to practical applications.

The project demonstrates that combining tangible interaction with guided learning activities can effectively support the understanding of abstract mechanical principles within engineering education.

Rather than replacing existing teaching methods, the Mechanical Garden is intended to complement lectures and design courses by providing students with a fast, accessible, and engaging way to explore mechanical systems through hands-on experimentation. The research therefore contributes both a validated educational product and practical design guidelines for developing future tangible learning tools within higher engineering education.



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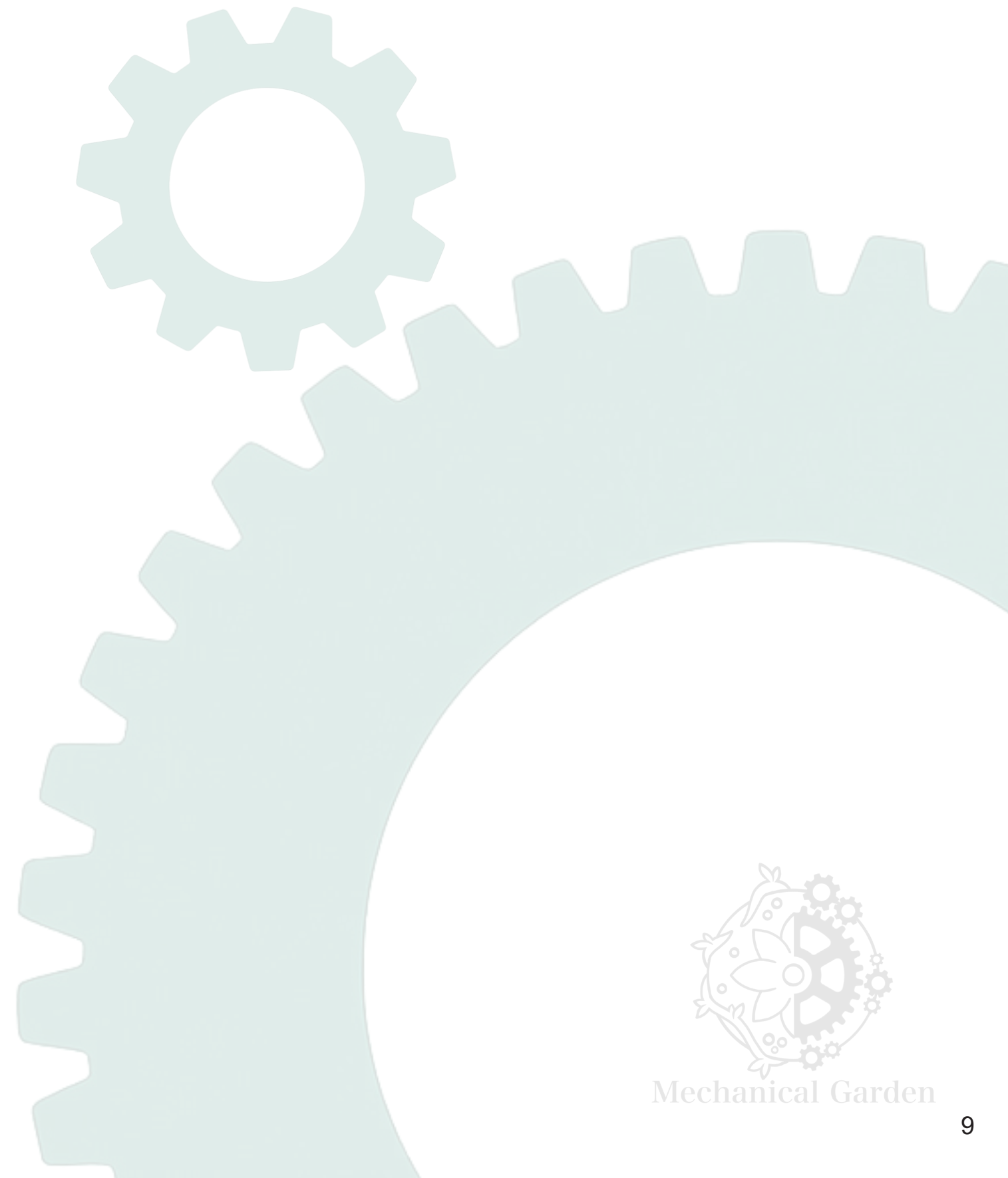
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Chapter 1.

Introduction

This chapter introduces the educational context and motivation of the project. It discusses the challenges associated with teaching and learning abstract mechanical principles within higher education and outlines the specific problems observed within the Industrial Design Engineering curriculum at TU Delft. Based on these challenges, the research aim, research question, and sub-questions are presented. Together, these elements establish the foundation for the development and evaluation of a learning tool intended to support students in understanding mechanical principles through physical interaction and experimentation.



1.1 Project background

University students are exposed to a large amount of theoretical and practical knowledge throughout their education. While some subjects are effectively internalized, others are often studied only temporarily in order to pass assessments and are therefore forgotten shortly afterwards. Adding to this is, some concepts are more abstract, making it difficult for the student to fully understand (Funkhouser & Nicoladis, 2023)

This challenge becomes increasingly relevant when also looking at the educators, who are expected to teach growing amounts of content to increasingly larger groups of students (Coorey, 2016). Within design education specifically, educators are frequently required to balance theoretical instruction with practical and technical learning (Coorey, 2016). At the same time, students entering higher education possess diverse educational backgrounds, learning styles, and personal preferences (Romanelli et al., 2009). As a result, a single method of teaching is often insufficient to support all students effectively.

Traditional educational environments commonly rely on lectures, slides, and textbooks, positioning students in relatively passive roles during the learning process. This can become particularly problematic when teaching subjects that could benefit from physical examples. Mechanical movements and mechanisms, for example, are often difficult to fully comprehend through two-dimensional representations alone.

Research suggests that abstract concepts can benefit from specific examples (Funkhouser & Nicoladis, 2023) and conventional teaching methods can be strengthened through the integration of physical learning tools that encourage active participation and engagement (Prabhavalikar & Patil, 2022). Tangible and interactive learning experiences may support students in developing a deeper understanding of complex mechanical principles by allowing them to physically explore movement, interaction, and cause-and-effect relationships.

In addition to the challenges identified in literature, the motivation for this project was influenced by my personal experience within the Faculty of Industrial Design Engineering at TU Delft. Over the past three years, I have worked as a teaching assistant in courses including Digital Interfaces, the Interactive Environments Minor, and Design Project 3 (DP3), supporting students during prototyping, testing, and development activities. Through this role, a strong interest developed in the ways students learn through making, experimentation, and physical interaction.

As someone who is passionate about prototyping and building, this sparked a particular interest in exploring how hands-on learning experiences could be used to support the understanding of technical and mechanical concepts. This combination of educational challenges identified in literature and personal experience within design education formed the starting point for the project.

1.2 Problem statement

This project focuses on bachelor students within the Faculty of Industrial Design Engineering at TU Delft. Throughout their education, students are required to apply technical and mechanical principles within design projects. While theoretical knowledge regarding these principles is provided throughout the curriculum, observations made over three years while working as a teaching assistant suggested that applying this knowledge in practice is often challenging.

Students were frequently observed wanting to incorporate movement and interaction into their projects while simultaneously struggling to identify and prototype suitable mechanical solutions. In many cases, intended movement could not be translated into technically feasible mechanisms. Furthermore, students often appeared unaware of the variety of existing mechanical principles and mechanisms that could potentially support their design intentions.

As a result, students may encounter difficulties when designing, prototyping, and evaluating products involving mechanical movement. This suggests that a gap may exist between the theoretical knowledge students acquire during their education and their ability to apply this knowledge within a practical design context.

Since understanding and applying mechanical principles is an important aspect of engineering and design practice, these difficulties may affect students' ability to develop technically feasible design solutions and make informed design decisions. The observations described above formed the starting point of this project and motivated further investigation into how students learn, understand, and apply mechanical principles within design education.

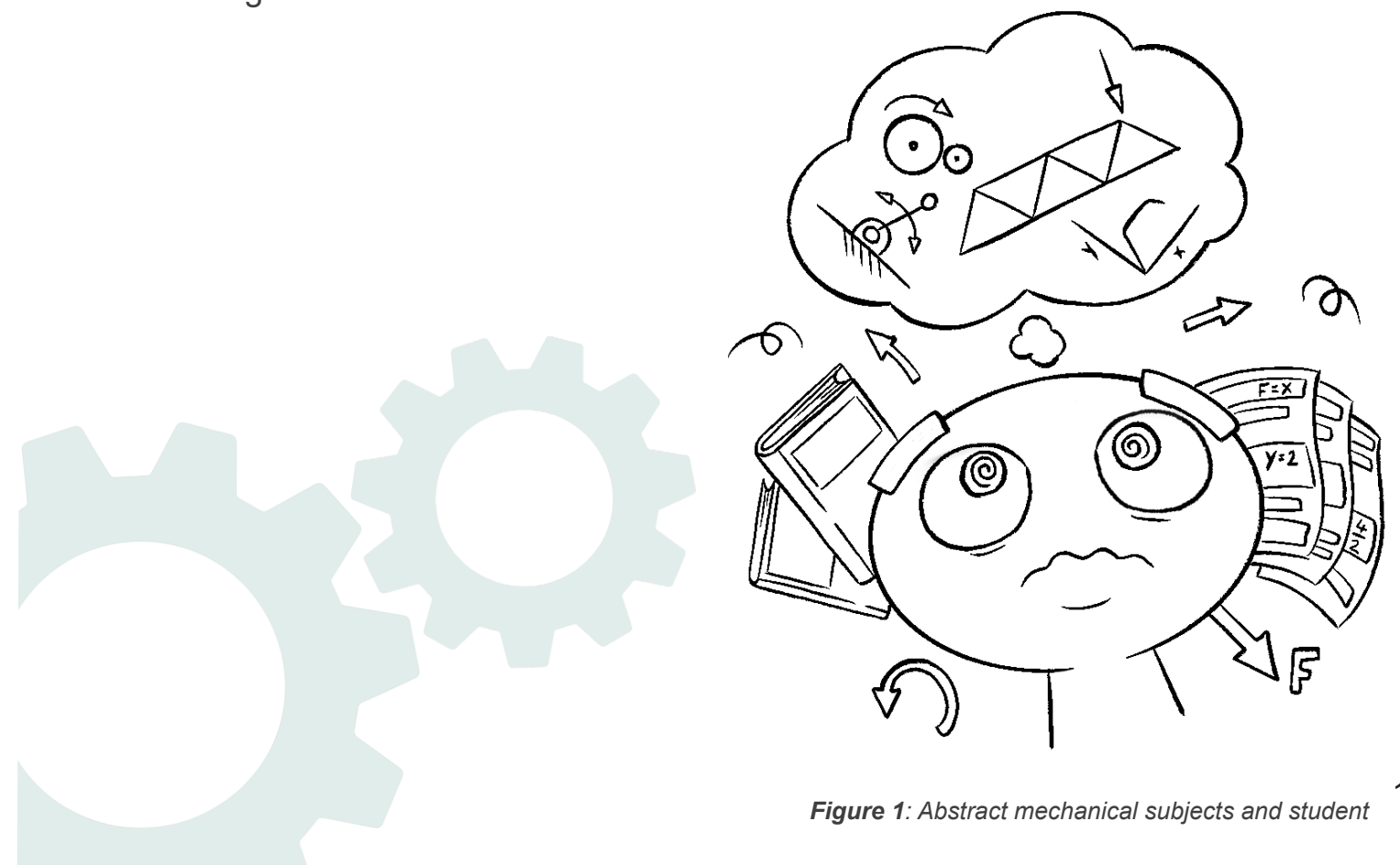


Figure 1: Abstract mechanical subjects and student

1.3 Project objective

The objective of this project is to design, develop, and evaluate a tangible learning tool that supports Industrial Design Engineering students in understanding and applying mechanical principles within a design context. The tool should provide students with opportunities to actively experiment with mechanical systems, explore different mechanisms, and receive immediate visual feedback on the consequences of their design decisions.

Rather than replacing existing educational methods, the learning tool is intended to function as an addition to the current curriculum. By complementing lectures, assignments, and design projects, it aims to support students in developing a more intuitive understanding of mechanical movement and strengthen their ability to translate theoretical knowledge into practical design solutions.

1.4 Research question

Based on the identified educational challenges and the limited opportunities for hands-on experimentation within the current curriculum, this thesis investigates how a learning tool, which stimulates physical interaction, may support students in understanding mechanical principles. The following research question and sub-questions were formulated to guide the development and evaluation of the proposed learning tool.

1.4.1 Main research question

How can physical and interactive learning tools support Industrial Design Engineering students in moving from abstract knowledge to intuitive understanding of mechanical principles?

1.4.2 Sub research question

- Which mechanical principles are experienced as most difficult to understand by Industrial Design Engineering students? How do students currently learn and internalize these principles?
- What role does physical interaction play in developing understanding of mechanical principles?
- How can a product be designed to stimulate active experimentation rather than passive observation?
- How do Industrial Design Engineering students currently learn and apply mechanical principles within the design process?
- Does adding a physical learning tool to existing courses such as DP3 support students in understanding and applying mechanical principles.

The following chapters explore and explain the theoretical foundation, design process, development, iterations and evaluations of the proposed learning tool and its previous versions.



1.5 Scope

DP3 is a course within the Bachelor Industrial Design Engineering programme at TU Delft. During the course, students are required to design, prototype, and evaluate functional robotic systems. The central theme of the course changes annually depending on the educational focus. Previous editions have explored topics such as agricultural robotics, while the 2026 edition focuses on robotic systems for the construction sector.

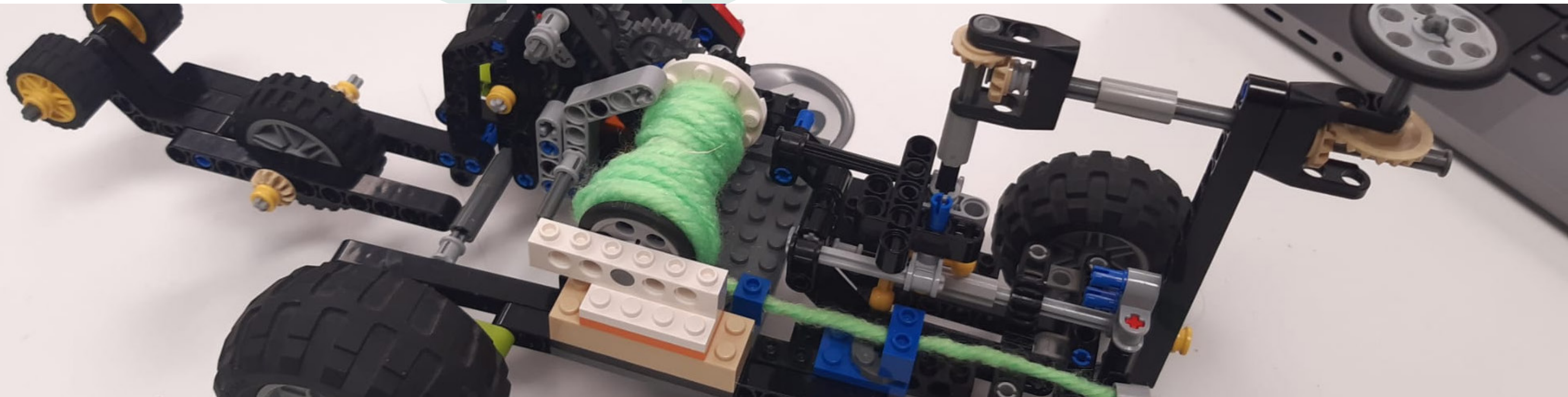
The course was selected as the primary context for this project for two reasons. First, DP3 requires students to apply a variety of mechanical principles, including motion transfer, gearing, movement conversion, and mechanism design. Second, at the start of this graduation project, the author was actively involved in the course as a teaching assistant. This provided direct

access to the educational environment, making it possible to observe students during the design and prototyping process and discuss educational challenges with both educators and industry professionals involved in the course.

Although the project is situated within the context of DP3, the scope is not limited exclusively to this course. The resulting learning tool is intended to support the understanding and application of mechanical principles more broadly within the Industrial Design Engineering curriculum. DP3 is therefore used as a representative context in which the educational challenge becomes visible and can be investigated.



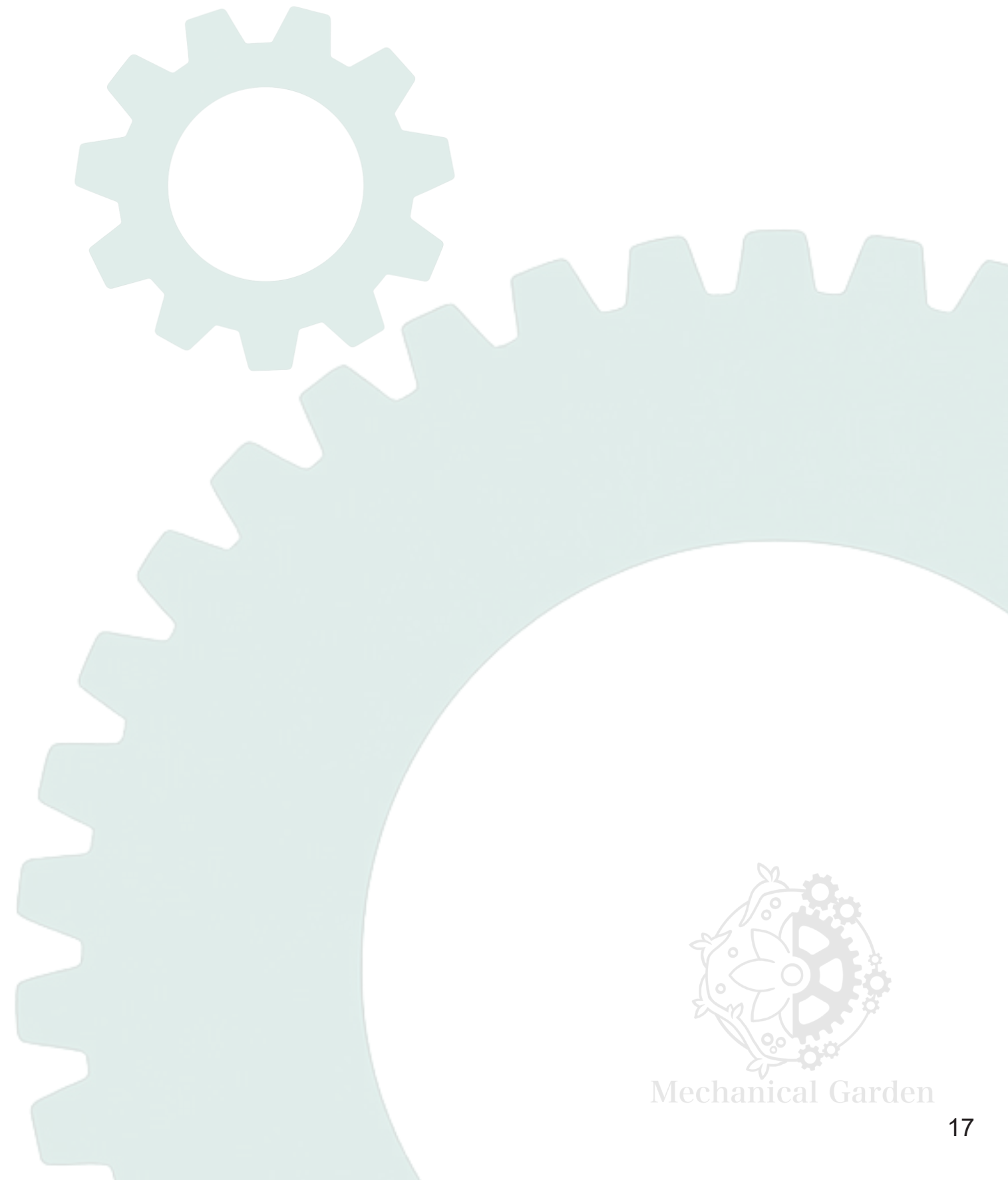
Figure 2: Prototyping activities, materials and results during DP3



Chapter 2.

Literature review

This chapter explores the theoretical foundation of the project. First, challenges related to technical education and the learning of abstract concepts are discussed. Subsequently, literature regarding physical interaction, tangible learning, and the understanding of mechanical principles is reviewed. Existing educational learning tools are analysed and the context of the DP3 course within the Industrial Design Engineering curriculum is introduced. Finally, the chapter identifies the research gap that motivates the development of the Mechanical Garden learning tool.



2.1 Context insights

The initial insights for this project originated from experiences gained over several years while working in various courses within the Faculty of Industrial Design Engineering. Through these experiences, recurring challenges and problems were observed regarding prototyping and the application of theoretical knowledge within design projects.

This chapter discusses these observations and compares them with findings from educator interviews.

At the start of this graduation project, the I was actively involved as a prototyping teaching assistant within Design Project 3 (DP3). This provided the opportunity to further observe students throughout the design, prototyping, and testing process, as well as discuss observed challenges with educators involved in the course.

Since these observations originated from personal experiences within the educational context, interviews with five educators were conducted to determine whether similar challenges were recognised elsewhere within the curriculum and to confirm if the observations were just a one time occurrence or were observed and happened more frequently. Keypoints from the interviews are added in Appendix A.

The interviews were intentionally open in nature, allowing educators to discuss their experiences with student learning, technical understanding, and the application of abstract concepts within design projects. Particular attention was given to how educators perceived students' understanding and application of technical and mechanical principles.

The observations and educator interviews revealed several recurring themes, which are presented in this section.

Observation 1

Students struggle to translate intended movement into technically feasible mechanisms.

During observations within DP3, Digital Interfaces, and the Interactive Environments Minor, students were frequently observed wanting to incorporate movement and interaction into their projects. However, many struggled to translate this intended functionality into technically feasible mechanical solutions.

This observation was supported by educator interviews. Several educators indicated that students often experience difficulties applying theoretical concepts such as vectors, moments, forces, and mechanical principles within design projects and new contexts.

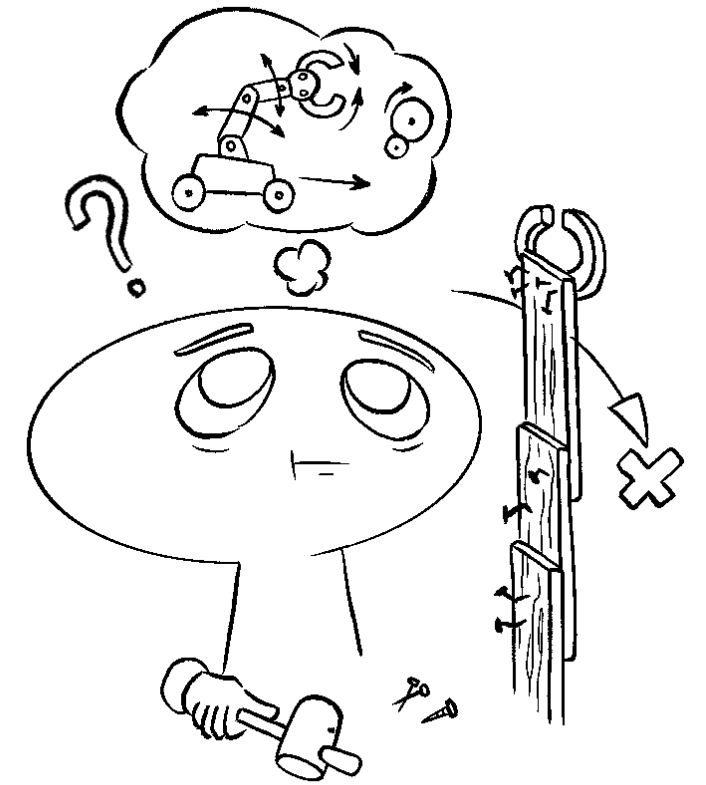


Figure 3: Visual highlighting observation 1

Observation 2

Students struggle to develop an intuitive understanding of mechanical behaviour.

Students were often observed experimenting through trial and error without fully understanding why mechanisms behaved in a certain way. As a result, physically impossible or ineffective solutions were frequently proposed.

This observation was supported by educator interviews, which indicated that students often have difficulty visualising abstract concepts such as moments, forces, deformation, and mechanical behaviour.

Educators further noted that students frequently fail to recognise when calculated outcomes are physically unrealistic.

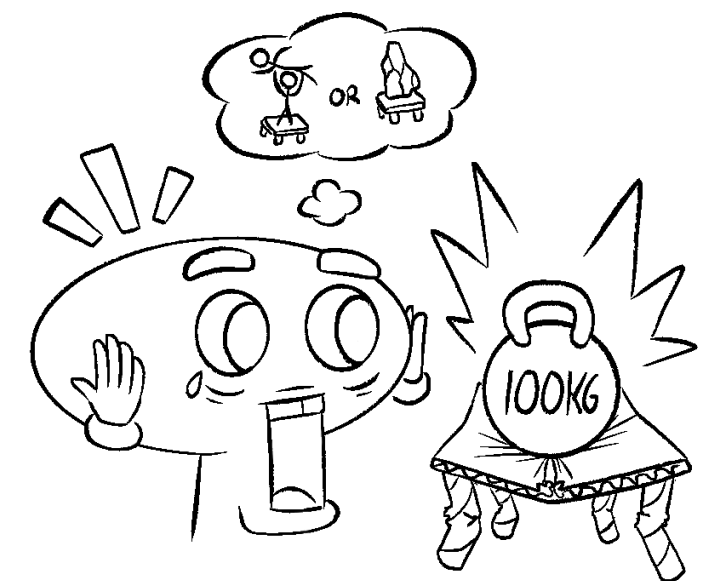


Figure 4: Visual highlighting observation 2

Observation 3

Students learn through making and experimentation.

Throughout the observed courses, students frequently gained understanding by building, testing, modifying, and discussing prototypes rather than solely through theoretical instruction.

This observation was strongly supported by educator interviews. Multiple educators emphasised that practical experimentation, productive failure, physical demonstrations, and hands-on interaction are highly effective ways of learning scientific and technical concepts.

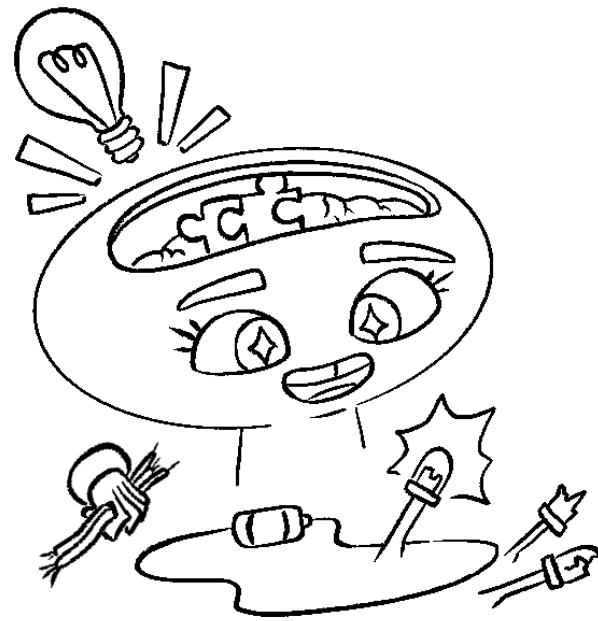


Figure 5: Visual highlighting observation 3

Observation 4

Students have difficulty prototyping and limited time to construct and experiment with prototypes.

During the observed courses, students were frequently found to experience difficulties creating and evaluating mechanical prototypes. As a result, students were often required to balance the time spent constructing prototypes with the time available for experimentation and exploration. Some ideas and mechanical solutions were therefore not prototyped or explored further because the effort required to realise them exceeded the time available within the project.

This observation was supported by educator interviews. Educators similarly indicated that practical, build-based learning has become increasingly difficult to facilitate within current educational settings, stating one of reasons being the increased number of students.

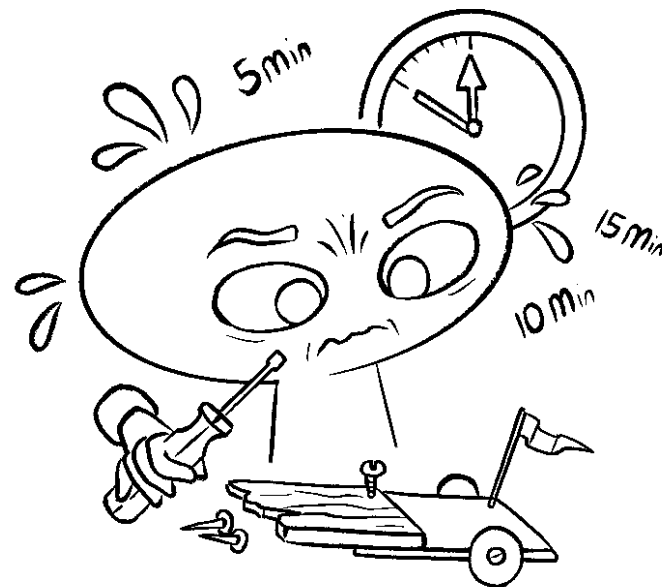


Figure 6: Visual of observation 4

Taken together, the observations and educator interviews suggest that students experience difficulties understanding, applying, and experimenting with mechanical principles within design projects. While students frequently require movement and interaction within their designs, limitations in technical understanding, prototyping ability, and available time may reduce opportunities for exploration and learning. These findings formed the basis for the subsequent literature review and informed the focus of this project.

2.2 Challenges in technical education

Currently, universities and higher education institutions often transfer knowledge through large-group lectures in which information is primarily communicated through slides, text, and theoretical explanation (Klein et al., 2023).

While effective for communicating information to large groups of students, this educational approach may encourage passive learning, which is increasingly considered to be misaligned with contemporary educational approaches that emphasize active participation and applied understanding (Roberts, 2017).

Within technical education, students are frequently required to understand abstract concepts and theoretical principles that lack a direct physical form, making them difficult to process and fully comprehend (Harpaintner et al., 2018). This challenge becomes particularly relevant when students are expected to apply these concepts within practical or design-oriented contexts.

Research suggests that the use of concrete, illustrative, and physical examples can support the understanding of abstract concepts and enhance learning outcomes (Deans for Impact, 2015; Nebel, 2020; Weinstein et al., 2018).

Tangible and interactive learning tools may therefore support students in translating abstract theoretical principles, such as mechanical movement, into more applied and intuitive understanding.

Figure 7: Lecture hall. (Hall T - Joost van Der Grinten, n.d.)



2.3 Learning through physical interaction

Educational approaches involving physical interaction and hands-on engagement have increasingly gained attention within learning research. Tangible learning environments use physical interaction, movement, and manipulation to support the understanding of abstract concepts through experiential engagement rather than purely theoretical instruction (Kazanidis et al., 2018).

In recent years tangible learning and tangible learning tools have received more attention. Research even suggests that tangible learning tools may positively influence the learning process by influencing learning behaviour and improving students' emotion during learning activities (Li et al., 2022). Through physical interaction and experimentation, students may develop a more applied and embodied understanding of abstract principles.

Within technical and design education, these approaches may be particularly relevant when students are required to understand spatial relationships, mechanical movement, and cause-and-effect interactions. Hands-on educational tools and interactive learning environments can support students in physically exploring concepts that are otherwise difficult to visualize through theoretical explanation alone.

Studies and implementations have shown that introducing hands-on tools also make it possible to teach subjects to an entire spectrum of students no matter their individual learning styles (Wood et al., 2005).

To further explain the importance and effect of actively interacting with a certain theory, subject or hands-on tool, embodied cognition literature suggests that the movements and actions we perform and are performed around us shape how we process and understand information (Sullivan, 2018). It is essential for engineering education to integrate, develop and iterate innovative tools which can replace conventional teaching/learning techniques (Prabhavalikar & Patil, 2022b).

Physical manipulatives, defined as physical objects that students can interact with and manipulate during the learning process, supports students in developing conceptual understanding by allowing them to physically visualize and explore abstract mechanical concepts that are otherwise difficult to understand through theoretical explanation alone (Mejia et al., 2016).

Therefore, designing a tangible interactive learning tool for DP3 may support similar forms of engagement, experimentation, and conceptual understanding.

One of the interviewed experts mentioned the value of hands-on on physical learning tools. even stating that it is one of the most effective means of teaching certain principles. However, it was also mentioned that increasing amount of students makes it more and more difficult to implement hands on learning.

2.4 Understanding mechanical principles

Students of different ages and abilities continue to experience difficulties in understanding subjects such as mechanics, electricity, heat, and optics, despite receiving traditional forms of instruction (McDermott, 1984).

These difficulties can be observed over many courses and studies. Research conducted in a university-level introductory material science course in which students were observed to have difficulties by mixing up different similar concepts, reasoning and using inappropriate models or analogies (Student Difficulties With Basic Concepts in Introductory Materials Science Engineering, 2011).

The fact that these difficulties keep occurring, suggests that conventional teaching approaches may not sufficiently support students in developing a deeper understanding of technical principles. Despite living in a digital age, physical tools and models are still being used

as representations of designs and/or concepts and are still viewed as valuable resources.

Research in spatial understanding found that interaction with physical models enabled participants to interpret spatial information more accurately and efficiently than digital representations (Sun et al., 2014).

Although this research was conducted in the context of spatial planning, the findings may be relevant to mechanical education, where students are also required to reason about the position, movement, and interaction of components in three-dimensional space.

This suggests that physical representations could support understanding of mechanical systems that are difficult to interpret through static representations alone.

2.5 Physical learning tools in higher education

A variety of educational tools and construction systems have been developed to support hands-on learning and help students better understand technical and mechanical principles.

Examples such as LEGO Technic/Education SPIKE, Fischertechnik, PASCO engineering demonstrators, TECQUIPMENT simple machines, AMATROL mechanical systems training systems, Meccano, and other mechanical demonstrator kits allow students of different ages and skill levels to physically explore concepts such as movement, gearing, construction, and force interaction through active experimentation (LEGO Education SPIKE, n.d.; STEM Mechanics, n.d.; PASCO Scientific, n.d.; TecQuipment, 2019; Amatrol, 2026; Meccano, 2026) figures 8, 9 and 10 show some of these systems.

Although not all of these systems are specifically designed for higher education, many have been used within engineering and technical courses in higher education to support practical and experiential learning. Systems such as previously mentioned LEGO Technic have been used in university programs to offer a hands-on experience (Ringwood et al., 2004).

Fischertechnik systems also have been implemented within university-level engineering education to support hands-on learning through physical experimentation and interaction with technical systems (Gensheimer et al., 2020).

Through construction, experimentation, and direct interaction, these tools allow

students to explore mechanical principles in a tangible manner that may be difficult to achieve through theoretical instruction alone.

Despite the educational value of these systems, they are not widely integrated within current curricula, such as the bachelor curriculum at the Faculty of Industrial Design Engineering at TU Delft (Bachelorprogramma Industrieel Ontwerpen, n.d.). While these tools successfully support the construction and demonstration of mechanical systems, many remain strongly focused on modular or grid-based building approaches. Although such structures simplify assembly and increase accessibility, they may limit students' freedom to directly explore underlying mechanical principles or create alternative solutions outside the predefined system.

As a result, students are often required to first construct a model before meaningful experimentation with movement and interaction can take place. Furthermore, many systems rely on predefined modules and connection methods, which may reduce flexibility during rapid exploration and iterative experimentation. Within fast-paced design courses, students do not always have sufficient time available for extensive construction and setup before experimentation can begin.

To summarize, despite the availability and educational value of many existing learning tools, no comparable tools were identified within the Industrial Design Engineering bachelor curriculum at TU Delft. This suggests that opportunities remain to develop a learning tool that

better supports the needs of IDE students in understanding and experimenting with mechanical movement.

Opportunities therefore remain to design and create a fitting learning tool that

allow students to rapidly and intuitively experiment with mechanical movement while minimizing construction effort and setup time and adding design-based interaction such as designing your own pieces to add to the learning tool.



Figure 8: PASCO simple machines engineering kit. (Hanna, z.d.)

Figure 9: Lego spike. (Wat Is Dit?, z.d.)

Figure 10: TECQUIPMENT, cam, crank and toggle kit. (CAM, CRANK AND TOGGLE KIT, z.d.)

2.6 Research gap

To summarize, students experience difficulties with abstract subjects such as mechanical movement. Interviews with educators and observations within the IDE curriculum indicated that these difficulties are also experienced by Industrial Design Engineering bachelor students. Research suggests that active learning, physical interaction, and tangible learning tools may improve students' understanding of mechanical principles.

Interactive hands-on learning tools do exist and are being used within higher education. For example, LEGO Mindstorms has been used in engineering design education to provide students with hands-on experience in designing and prototyping robotic systems (Ringwood et al., 2004).

Despite the existence of such approaches in engineering education, no comparable learning tools were identified within the Industrial Design Engineering bachelor curriculum at TU Delft during the observations, educator interviews, and curriculum exploration conducted as part of this project.

The fact that educators at IDE do observe and experience a knowledge gap in students in the subject mechanical movement would suggest that such a tool could prove to be beneficial for the overall understanding of mechanical movement by the student.

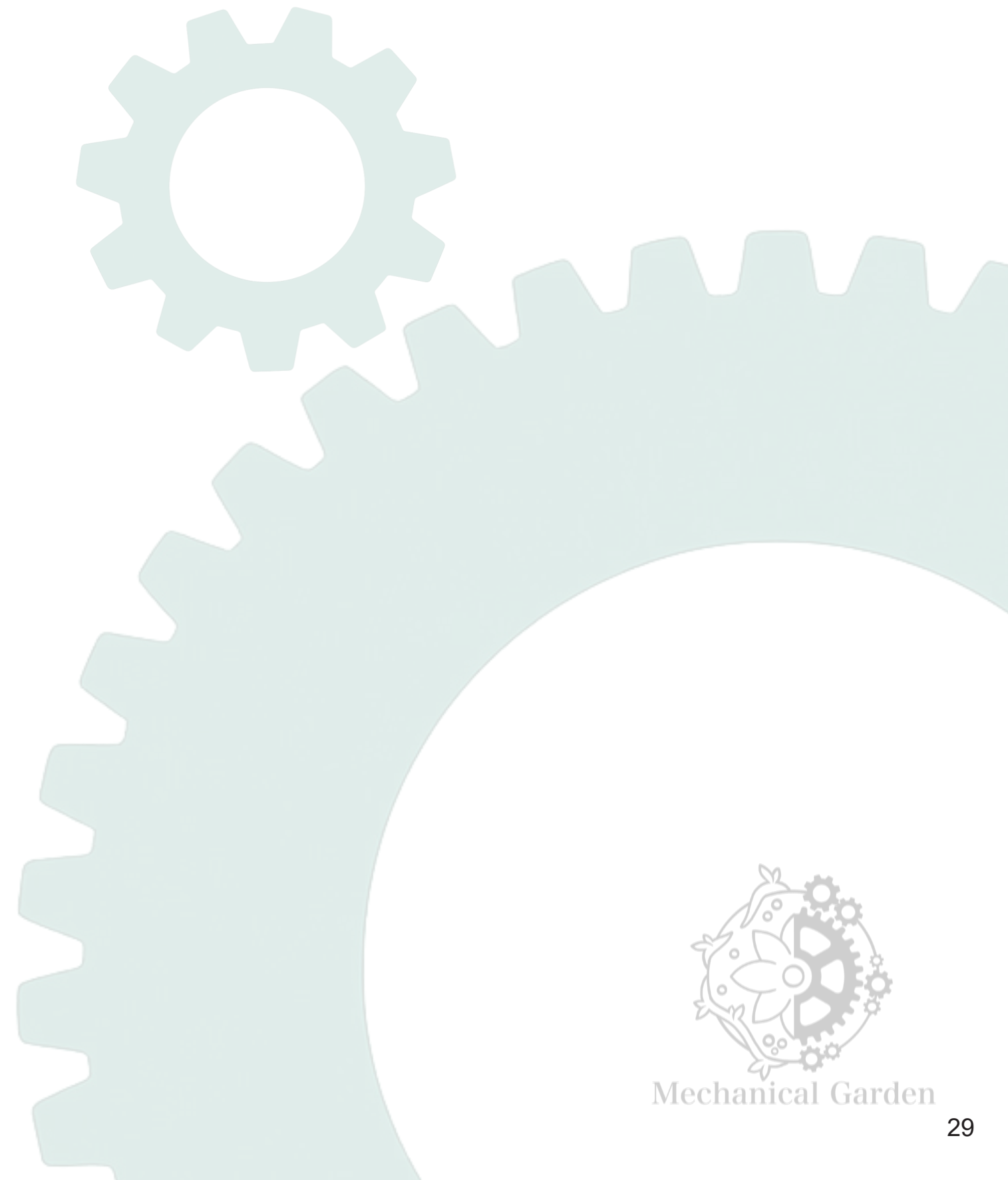
However, no existing learning tools focusing on mechanical movement are in use at the IDE bachelor at the time of writing this thesis. This suggests that existing tools may not fully address the needs of Industrial Design Engineering students within the context of the current curriculum. Several factors may explain why this is the case, including construction time and limited creative freedom.

That is why this project will focus on creating a learning tool for IDE bachelor students with which they will have hand-on experience with mechanical mechanisms which fit the IDE curriculum. Specifically the bachelor students in the context of the DP3 course.

Chapter 3.

Methodology

This chapter describes the research methodology and design approach used throughout the project. It explains why a Research-through-Design approach was selected and outlines the research activities conducted to answer the research questions. Furthermore, the chapter discusses the iterative design process, the transition towards a stronger Research-through-Design methodology, and the overall development process followed during the project.



3.1 Research approach

This project follows a Research-through-Design approach. Within this approach, knowledge is generated through the iterative creation and evaluation of design artefacts and prototypes. The knowledge gathered from testing these artefacts contributes to the overall research process and helps inform subsequent design decisions (Stappers & Giaccardi, 2017).

This approach was chosen because the project aimed to develop a physical learning tool that enables students to independently explore, experiment with, and understand mechanical principles. Since the project focused on learning through physical interaction, experimentation, and active engagement, physical artefacts were required to investigate different interaction principles and educational approaches.

Furthermore, Research-through-Design allows multiple design directions to be explored through iterative prototyping, making it particularly suitable for projects in which the final solution is not known from the outset (Stappers & Giaccardi, 2017). Due to the multidisciplinary nature of the project, it was considered

beneficial to explore multiple concepts and interaction approaches before converging on a final design direction.

This was achieved through the iterative creation, evaluation, and refinement of prototypes. By continuously designing, testing, and improving artefacts, different concepts, interaction principles, and learning experiences could be investigated in practice. The insights generated during each iteration informed subsequent design decisions and gradually contributed to a more focused and informed design direction.

An additional advantage of the Research-through-Design approach was that the development of prototypes generated insights beyond user interaction and educational value. The process of designing and manufacturing prototypes provided practical knowledge regarding material selection, production methods, assembly, technical feasibility, and physical embodiment. These insights contributed directly to the development and refinement of the final Mechanical Garden prototype.

3.2 Research activities

To answer the previously stated research questions mentioned in Chapter 1.4 and generate new knowledge on how to design and develop a fitting learning tool for Bachelor IDE students specifically focusing on the course DP3.

Several research activities were conducted. To ensure a relevant starting point for R&D. This chapter will discuss the conducted research activities during this project and the importance of these activities regarding the project. The activities and related research questions can be observed in Table 1.

Activity	Purpose	Output	Related research question
Literature review	Research and discover the underlying educational challenges.	Theoretical foundation and academic understanding.	RQ1, RQ2, RQ3, RQ4
Educator interviews	Identify educational challenges observed by lecturers and gain insight into current teaching practices and curriculum limitations.	Educational insights	RQ1, RQ2
Student interviews/survey	Identify which mechanical and technical concepts students find difficult to understand, apply, and retain.	User insights	RQ1, RQ2
Observations	Understand the behaviour of the students. Observing how physical making is utilised by the student and how this could be improved.	Contextual insights	RQ2
Prototyping	Explore and evaluate different design directions through iterative development.	Design directions	RQ4
Prototype testing	Testing and evaluating physical, interactive and educational attributes of the prototypes.	Feedback regarding the design.	RQ3, RQ4
Design and construction	Discover the best material, production methods and feel,	Well balanced and thought out design.	RQ1

Table 1: Activities and related research questions.

To summarize, the literature review provided the theoretical foundation for the project. Interviews with educators and students were conducted to identify educational challenges and opportunities within the current curriculum. Observations were used to gain contextual insights regarding student behaviour and learning practices. Finally, iterative prototyping and prototype testing were employed to explore design directions and evaluate potential solutions.

3.3 Design process

Following the research activities such as literature reviews, interviews and surveys an iterative design process was conducted. Multiple prototypes were designed, developed, tested and refined through this process.

Alongside the development of these prototypes, professionals and literature were consulted when necessary. This was done to further explore material, production, finishing and learning techniques.

3.3.1 Transition towards Research-through-Design

The first phase of the project focused on understanding the educational challenge. Multiple educators from the Industrial Design Engineering faculty at TU Delft were interviewed to identify which technical and mechanical subject's students struggle with most Appendix A.

students to gain a better understanding of which subjects they experienced as most difficult to understand and apply in design projects.

Based on these interviews, a list of subjects was compiled and used to create a questionnaire Appendix B. This questionnaire was distributed among

Following this research, a design process was started involving sketches, concept generation, and methods from the Delft Design Guide. The resulting sketches and ideas can be seen in figure 11.

The generated ideas were grouped and eventually resulted in three possible design directions. Although this process provided a clearer understanding of the problem and several potential solutions, it also became apparent that choosing a single direction at this stage would be difficult.

Instead of further discussing concepts on a theoretical level, multiple prototypes were created and tested. This allowed ideas to be explored in practice and generated new insights regarding interaction, form, educational value, and usability.

The iterative process of creating, testing, and refining prototypes ultimately provided a clearer direction for the project and contributed significantly to the development of the final learning tool and answer the research questions.

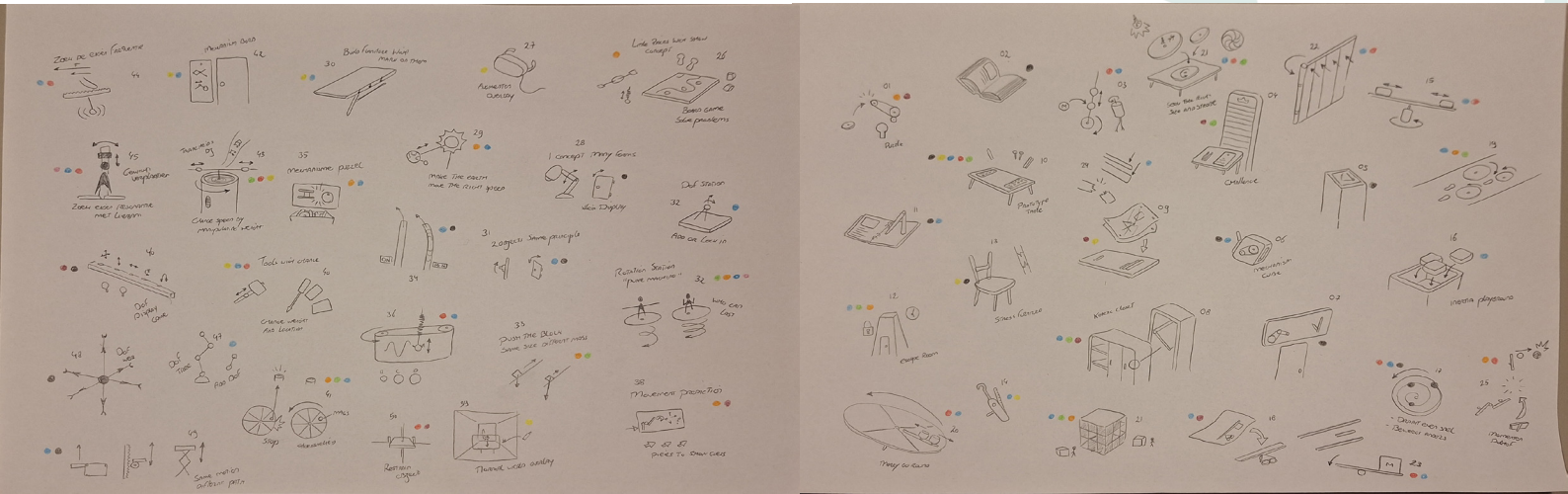
Many assumptions regarding interaction, learning behaviour, and the physical embodiment of the learning tool had not yet been explored or validated. Furthermore, the knowledge produced by the questionnaire proved to be inadequate. After discussing the results with educators, it was found that the students themselves could not effectively predict the level of understanding concerning a certain course subject.

Furthermore, the development of prototypes led to the emergence of new design questions that had not been identified during the initial research phase. These questions were subsequently investigated through additional research and experimentation, allowing the project to continuously adapt and evolve throughout the design process.

As a result, the project shifted towards a stronger Research-through-Design approach, an approach where knowledge is generated by combining user research and the creation of multiple prototypes (Research Through Design, n.d.).



Figure 11: Sketches and ideas



3.3.2 Design process overview

Figure 12, provides an overview of the complete design process followed throughout the project. This process is repeated for each developed prototype. The process started with a research phase focused on understanding the educational challenge. approach was adopted, resulting in the iterative development and evaluation of multiple prototypes. The insights generated during each iteration informed subsequent design decisions and ultimately contributed to the development of the final learning tool.

This was followed by concept generation and the exploration of several potential design directions. As the project progressed, a Research-through-Design

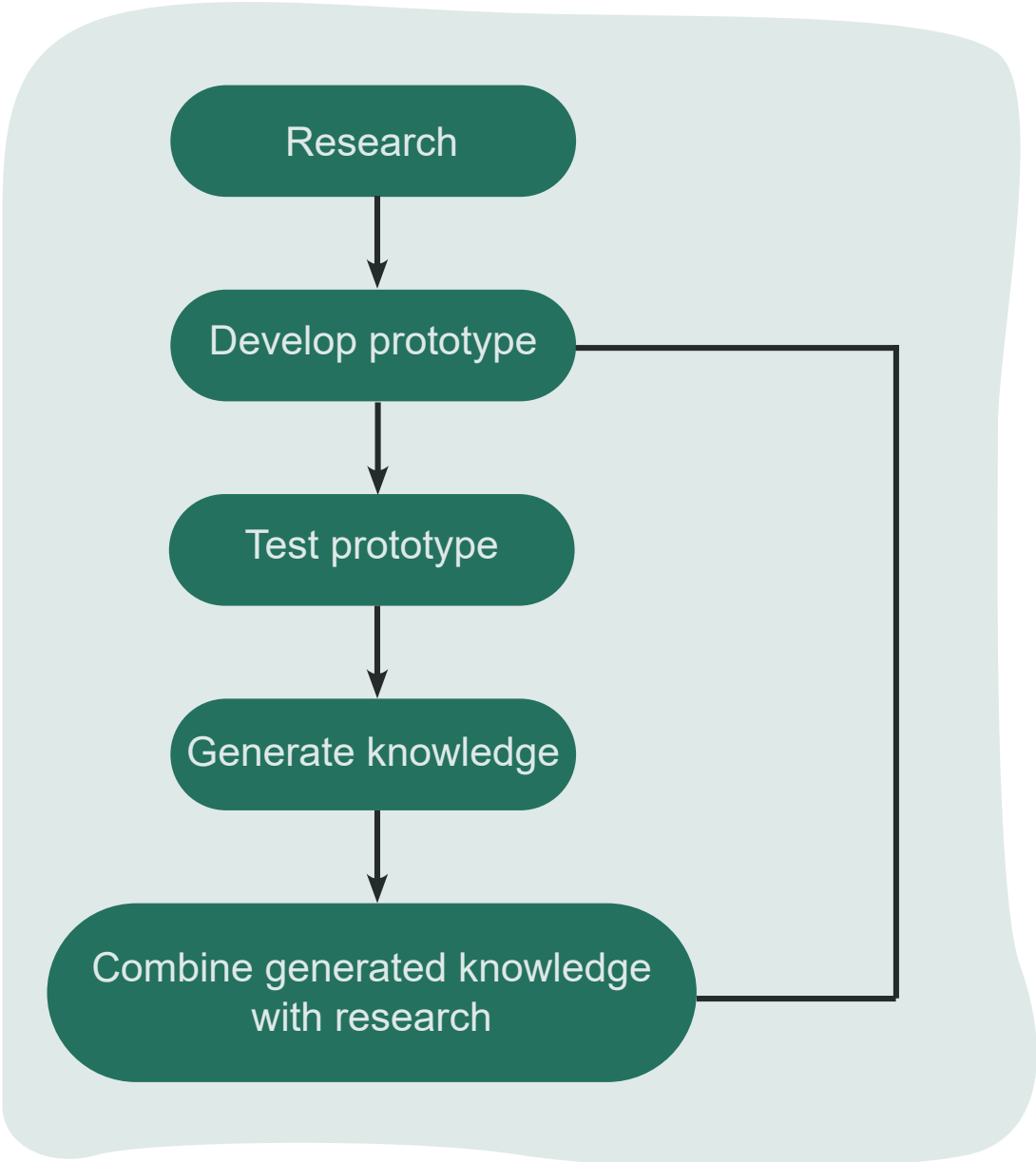


Figure 12: Overview followed design process

3.4 Evaluation strategy

Because the project follows a Research-through-Design approach, evaluation took place throughout the entire design process. Different prototypes were evaluated according to their intended purpose and the specific questions they were developed to answer.

The first phase of the project consisted of an experimental iterative process in which multiple different prototypes were designed and created. These prototypes generated valuable knowledge into how to design a learning tool. This explorations of he different prototypes and their findings can be found in Chapter 4.

Final prototype evaluation

The Mechanical Garden was evaluated to assess both its educational effectiveness and its functionality as a learning tool. The evaluation investigated whether interaction with the Mechanical Garden improved students’ understanding of mechanical principles and whether the system supported the intended learning activities.

During the explorative process, a promising design direction emerged and was further developed through multiple iterations. This design direction eventually became the basis of the final prototype, the Mechanical Garden learning tool. Detailed descriptions of these different prototypes, their detailed evaluations, findings and resulting design decisions are presented in Chapter 5.

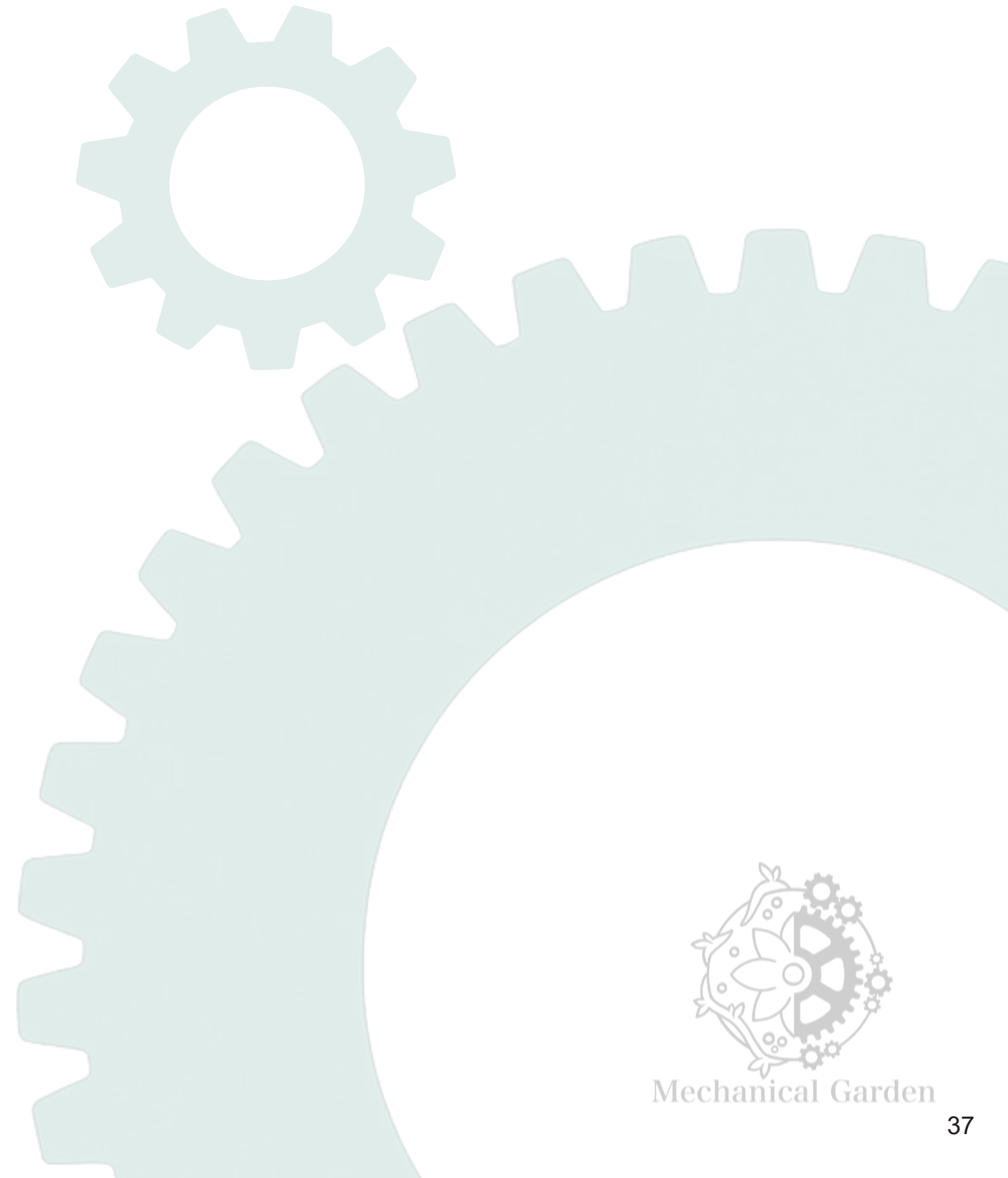
To assess these aspects, a mixed-method evaluation approach was used consisting of written tests, observations, questionnaires, and interviews. The combination of quantitative and qualitative methods provided insight into both learning outcomes and user experiences.

A detailed description of the evaluation procedure and results is provided in Chapter 6.

Chapter 4.

Exploration

This chapter presents the iterative development of the Mechanical Garden learning tool. Through a Research-through-Design approach, multiple prototypes were designed, tested, and refined to explore different educational and interaction possibilities. The chapter discusses the key design decisions, prototype evaluations, and insights that ultimately contributed to the development of the final. Mechanical Garden Prototype.



4.1 Prototype 01 – PuzzleTruss

Purpose

The purpose of this prototype was to investigate whether a physical challenge could increase student engagement and support understanding of a technical principle. It presented the students with a puzzle which would be based on one of the subjects found in the IDE bachelor at the TU Delft. This prototype specifically came from an interview with an educator who explained the importance of setting a challenge for the students. This challenge was realised as a simple puzzle which students were asked to solve. After solving the puzzle, the student would hopefully develop an understanding for the subject.

Prototype description

The prototype consisted out of a wooden board on which wooden bars were attached. These bars were oriented in a rectangle, two corners of the rectangle were permanently attached to the wooden board. The other two corners were not connected to the board making the construction if held upright unstable. Along side the rectangle a bar was hung from a piece of rope. This bar could be placed inside of the rectangle in multiple orientations. If the bar was placed incorrectly the construction would continue to be unstable, the right corner of the rectangle would fall downwards. If the student placed the bar in the correct orientations inside of the rectangle the construction would be stable and pressure could be applied to the construction by the student. Figure 13 shows the puzzle truss prototype.

Evaluation

The prototype was presented to multiple students who could interact with the puzzle prototype and try to solve it. During the interaction the students were asked to continuously describe their thought process and interaction with the prototype to the researcher.

Findings

During the interaction it became clear that the physical embodiment did provide students with a way of directly interacting with the prototype and the subject it tried to represent, however the puzzle was found to be too simple. Students found the concepts of puzzles based on learned subjects a fun addition to the courses, but did desire a bigger challenge and more opportunities of interaction.

Another problem which could arise from this prototype is that when the puzzle is solved it no longer provides a valuable learning opportunity for the student who solved it. It is a concept which provides learning the first time, but does not allow for own experimentation, experimentation and cannot be used after it is solved.

The evaluation suggests that physical challenges can stimulate engagement, but learning opportunities diminish when the solution space is limited and the outcome becomes predictable.

Reflection and design implication

The PuzzleTruss prototype was the first physical prototype constructed during this project. The evaluation revealed that challenge-based interaction can increase engagement with educational content. However, the static nature of the

puzzle limited opportunities for continued exploration and experimentation. The evaluation further revealed that the educational value of the prototype was limited to the single challenge presented to the user. Once the puzzle had been solved, there were few opportunities for continued learning, experimentation, or exploration.

This suggested that future learning tools should support repeated interaction and allow students to explore multiple solutions and mechanical principles rather than working towards a single predetermined answer.

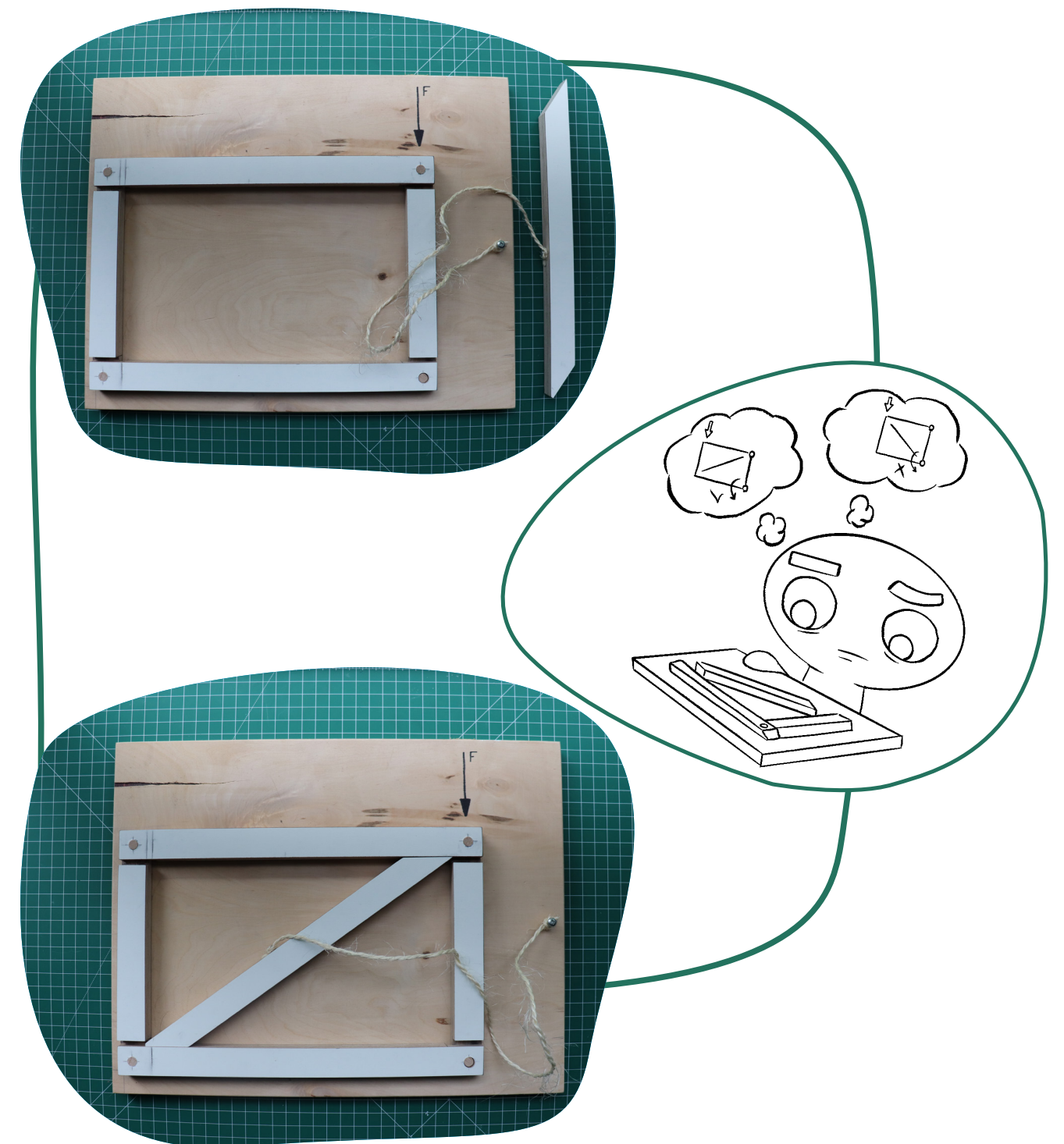


Figure 13: PuzzleTruss prototype and visual representation of interaction.

4.2 Prototype 02 – Pocket Construction Prototyper

Purpose

The Pocket Construction Prototyper was developed as an exploratory artefact investigating how physical prototyping could be made more accessible for students, by creating a physical prototype tool which was possible to carry on your person. During observations in several courses within the IDE curriculum, it became apparent that students often experienced difficulties when constructing prototypes. Building even simple concepts could require significant amounts of time, specialised materials, and manufacturing equipment. As a result, prototyping was sometimes perceived as a time-consuming activity rather than a tool for exploration and learning.

The purpose of this prototype was therefore to investigate whether a compact and portable construction system could support rapid prototyping and experimentation. The prototype was intended as a tool that students could easily carry with them and use alongside design and engineering courses.

Prototype Description

The prototype consisted of a 3D-printed PLA baseplate containing a grid of evenly spaced holes. A collection of specially designed components could be attached to the baseplate, allowing different structures and concepts to be assembled. The prototype focused primarily on construction possibilities and was inspired by courses in which students analyse and design simple beam and truss structures. By physically constructing these structures, students could potentially gain a more intuitive understanding of the behaviour of the systems they encountered in class. The prototype therefore explored

the relationship between physical construction, interaction, and learning. Figure 14 shows the Pocket construction prototyper, prototype.

Evaluation

This prototype was not evaluated with students. Instead, it functioned as an exploratory artefact that allowed the investigation of different construction principles, manufacturing methods, and interaction possibilities. The evaluation therefore focused on observations made during the design and construction process itself.

Findings

The development of the prototype revealed several practical limitations. Due to the small form, the system required a large number of individual components, increasing the risk of pieces being lost or damaged during use. Furthermore, the prototype relied on a grid-based construction principle. Although this allowed structures to be assembled quickly, it also introduced constraints regarding the placement and orientation of components.

The grid system limited the flexibility of the prototype. When new construction possibilities wanted to be explored, additional custom components had to be designed and constructed to fit the predefined dimensions of the system. As a result, the prototype supported rapid construction but offered limited freedom for adaptation and experimentation.

Reflection and design implications

Although the Pocket Construction Prototyper was not evaluated with

students, the prototype generated several valuable insights regarding the design of construction-based learning tools. The development process demonstrated that portability and rapid assembly can make physical prototyping more accessible. At the same time, the prototype revealed that construction systems based on predefined grids inherently limit flexibility and often require specialised components.

This insight would prove relevant throughout the remainder of the project. Future iterations should not only enable rapid construction, but also provide sufficient freedom for students to adapt, modify, and explore their own ideas without being constrained by a predefined structure. Balancing ease of use with freedom of experimentation.

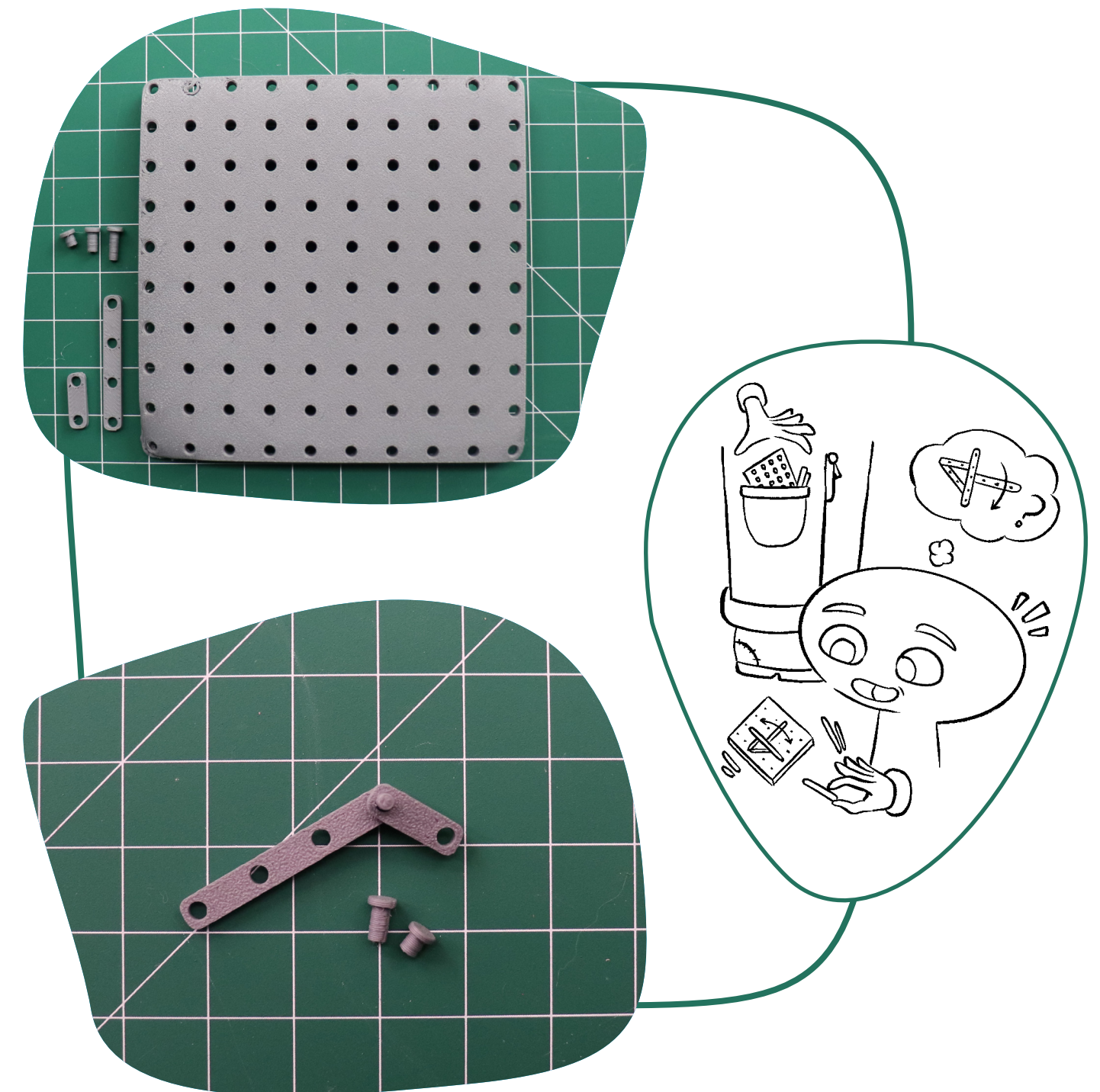


Figure 14: Pocket construction prototyper and visual representation of interaction

4.3 Prototype 03 – (after switch to RtD) – Book of Movement

Purpose

The first prototype developed after the transition towards a Research-through-Design approach was the Book of Movement. Interviews with educators, observations within the IDE curriculum, and personal experiences as a teaching assistant indicated that students often struggled to translate an intended movement into a suitable mechanical solution. One possible explanation for this difficulty was that students were unfamiliar with the variety of mechanisms available to them and therefore lacked a reference framework when designing mechanical systems.

The purpose of this prototype was therefore not to provide a complete technical understanding of mechanisms, but rather to investigate whether a tangible and interactive overview of commonly and trivial used mechanisms could increase students’ awareness and understanding of mechanical movement. The prototype focused on exposing students to different movement principles and allowing them to physically interact with these mechanisms in a simple and accessible manner.

Prototype Description

The prototype consisted of a booklet containing several 3D-printed mechanisms. Students could interact with the mechanisms by manually moving specific components and observing the resulting movement. Supporting information regarding the operating principle, construction, important characteristics, and possible applications of each mechanism was integrated into the booklet. Figures 15 and 16 show the book of movement and some of the mechanisms

As it was difficult to include all available mechanisms within a single prototype, a selection was made to represent different methods of converting, transferring, and controlling movement, allowing students to explore a broad range of mechanical principles commonly encountered in engineering and product design (Uicker et al., 2017).

The mechanisms were found using the previously mentioned source and following source, this presents a library of existing mechanical systems and offers

Mechanism	Explanation
Geneva mechanism	converts continuous rotational motion into intermittent movement.
Scotch yoke	converts rotational motion into reciprocating linear motion.
Ratchet mechanism	allows movement in one direction while preventing movement in the opposite direction.
Gear train	transfers and modifies rotational motion.
Cam and follower	convert rotational movement into controlled and programmable motion patterns.

Table 2: Chosen Mechanisms with small explanation.

the possibility to see these mechanisms in action in a virtual space (507 Mechanical Movements, n.d.). Table 2 presents the chosen mechanisms with a small explanation.

Evaluation

The prototype was presented to several students, who were given the opportunity to freely interact with the booklet before participating in a small interview and discussion. The evaluation focused on the educational value of the concept, the level of interaction, the opportunities for exploration, and the overall attractiveness of the learning experience.

Findings

The evaluation showed that students appreciated being introduced to a variety of mechanisms, many of which were previously unfamiliar to them. The combination of reading and physical interaction was generally perceived as a positive addition compared to purely theoretical learning materials. Students indicated that physically manipulating the mechanisms made it easier to understand how the different movement principles operated.

At the same time, several limitations became apparent. Although students could interact with the mechanisms, the interaction remained limited to observing and manipulating predefined examples. Once a mechanism had been explored, there was little incentive to continue interacting with the prototype or investigate alternative solutions. Several students also expressed a desire for more examples demonstrating how the mechanisms are applied in real products and engineering applications.

Another recurring observation was that the booklet primarily supported individual learning. Students described the prototype as a personal object rather than a tool that encourages collaboration, discussion, or experimentation within a group setting.

This suggested that the chosen embodiment primarily supported individual learning and exploration, limiting its potential as a collaborative learning tool. Since cooperative learning has been shown to improve student achievement and learning outcomes (Johnson et al., 2014), supporting simultaneous interaction by multiple students became an important consideration in the development of the Next iteration.

Reflection and Design Implications

The Book of Movement demonstrated that students were interested in physically interacting with mechanisms and that tangible representations of movement can support the understanding of mechanical principles. The evaluation suggests that physical interaction increases curiosity and engagement when compared to purely theoretical explanations.

However, the prototype also revealed an important limitation. While students could observe and experience mechanical movement, they were unable to actively manipulate the mechanisms beyond their predefined configuration. As a result, the interaction remained largely passive. Students gained awareness of different

mechanisms, but the prototype provided limited opportunities for experimentation, exploration, or the creation of new solutions.

This insight proved important for the continuation of the project. The evaluation suggested that introducing mechanisms alone was insufficient to support active Hands-on learning. Future iterations therefore needed to move beyond the presentation of mechanisms and instead provide students with opportunities to construct, modify, and experiment with mechanical systems themselves. Increasing the freedom to interact with and manipulate mechanical principles became a key design requirement for the next prototype iteration.

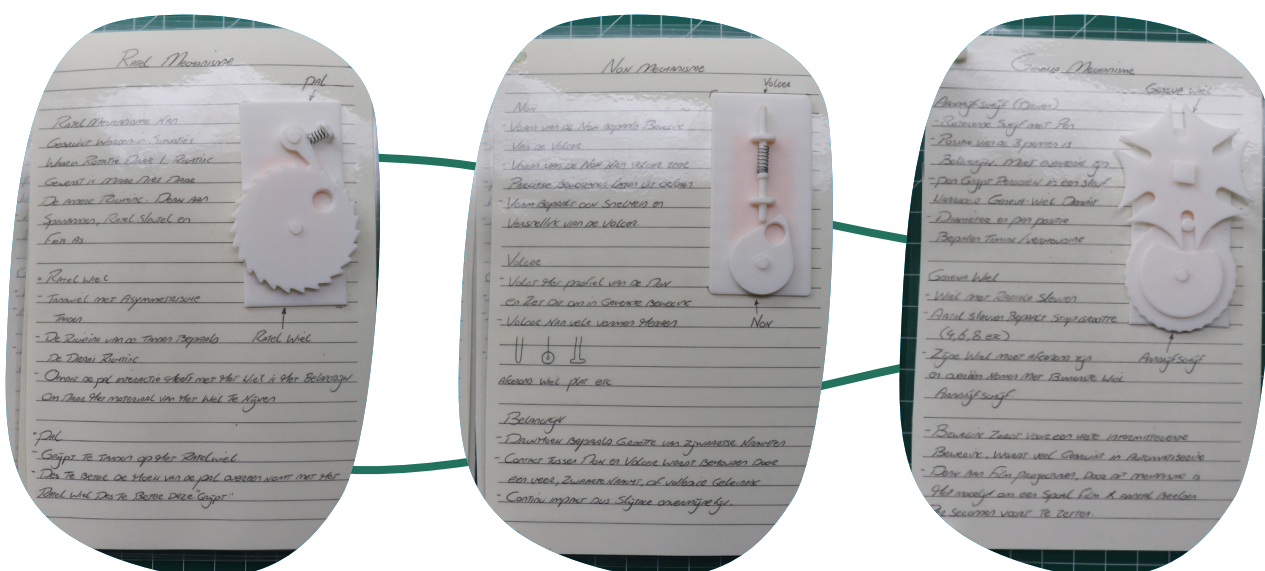


Figure 15: Photograph of some of the mechanisms found in the book of movement



Figure 16: Book of movement and visual representation of interaction

4.4 Prototype 04 – Mechanism Cartridge System

Purpose

The evaluation of the Book of Movement revealed that students appreciated physically interacting with mechanisms, but that the interaction remained largely passive. Although students could observe and manipulate predefined mechanisms, they were unable to modify, combine, or actively experiment with them. Increasing the level of interaction and freedom therefore became an important design requirement for the next prototype iteration.

The purpose of the Mechanism Cartridge System was to investigate whether students could become more actively involved in exploring mechanical principles by directly engaging with moving mechanisms. Rather than presenting mechanisms in a fixed format, the prototype aimed to encourage experimentation by allowing different mechanisms modules to be connected to a drive system.

Prototype Description

The prototype consisted of a wooden platform containing a large gear driven by a DC motor positioned beneath the surface. A gear train was incorporated to reduce the rotational speed, resulting in a slower and more controlled movement that could be easily observed by students. In front of the large gear, a track system was positioned. Different mechanical modules, referred to as cartridges, could be placed onto this track and slid towards the rotating gear. Once connected, the cartridges would engage with the drive gear, causing the mechanism to move. This allowed students to immediately observe the behaviour of different mechanisms and investigate the relationship between the driving gear and

the resulting movement. Figure 17 shows the Mechanisms cartridge system.

The track system itself was developed through several rapid prototyping iterations. Multiple small prototypes were produced to investigate different guiding mechanisms, eventually resulting in a print-in-place solution that combined ease of use with manufacturability which can be observed in figure 18.

Evaluation

The prototype was evaluated with several students. Participants were invited to freely interact with the system while verbalising their actions and reasoning. During the interaction, students were asked to describe what they were doing and why they chose certain actions. After the session, participants took part in a small interview and participated in a discussion regarding their experience.

The evaluation focused on:

- level of interaction
- educational value
- opportunities for experimentation
- freedom of use
- technical functionality of the system

Findings

The evaluation showed that the prototype successfully increased the level of interaction compared to the Book of Movement. Students appreciated the possibility of directly engaging with the mechanisms and observing their movement in real time. The immediate visual feedback provided by the rotating mechanisms stimulated curiosity and encouraged experimentation.

Several students also indicated that the ability to design and create their own cartridges could be a valuable addition. This suggested that the prototype had the potential to move beyond observation and towards active construction and exploration.

However, several limitations became apparent during the evaluation. Although the cartridge system increased interaction, it provided little information regarding the underlying mechanical principles. Students could observe movement, but additional support was required to understand why the mechanisms behaved in a certain way. Several participants expressed a desire for more educational content and explanations. The physical embodiment of the prototype also imposed limitations. The single-track configuration restricted the number of mechanisms that could be explored simultaneously and limited the complexity of interactions between mechanisms. In addition, the cartridges could move away from the driving gear during use, reducing reliability and consistency of movement.

From a user perspective, students indicated a desire for greater freedom to create their own movements and explore alternative configurations.

Furthermore, the prototype proved difficult to use collaboratively, as only a limited number of students could effectively interact with the system at the same time. This was caused because of the size of the system and the fact that only one mechanism cartridge could be slid to the drive gear.

Reflection and Design Implications

The Mechanism Cartridge System demonstrated that increasing the level of physical interaction can stimulate engagement and encourage students to actively explore mechanical movement. Compared to the Book of Movement, the prototype shifted the learning experience from observation towards experimentation.

At the same time, the evaluation revealed that interaction alone was not sufficient to support learning. Students were interested in manipulating the mechanisms but also required information and guidance to understand the underlying principles. This suggests that effective learning tools should not only provide opportunities for experimentation but should also support reflection and understanding of the observed behaviour.

The evaluation also highlighted the importance of freedom within the learning experience. Students repeatedly expressed a desire to create their own movements and investigate alternative solutions. As a result, increasing configurability and reducing physical constraints became important design requirements for subsequent iterations. These findings indicated that future prototypes should provide students with greater freedom to construct and modify mechanisms while simultaneously supporting the learning of the underlying mechanical principles. The next prototype therefore focused on increasing modularity, flexibility, and opportunities for open-ended experimentation.

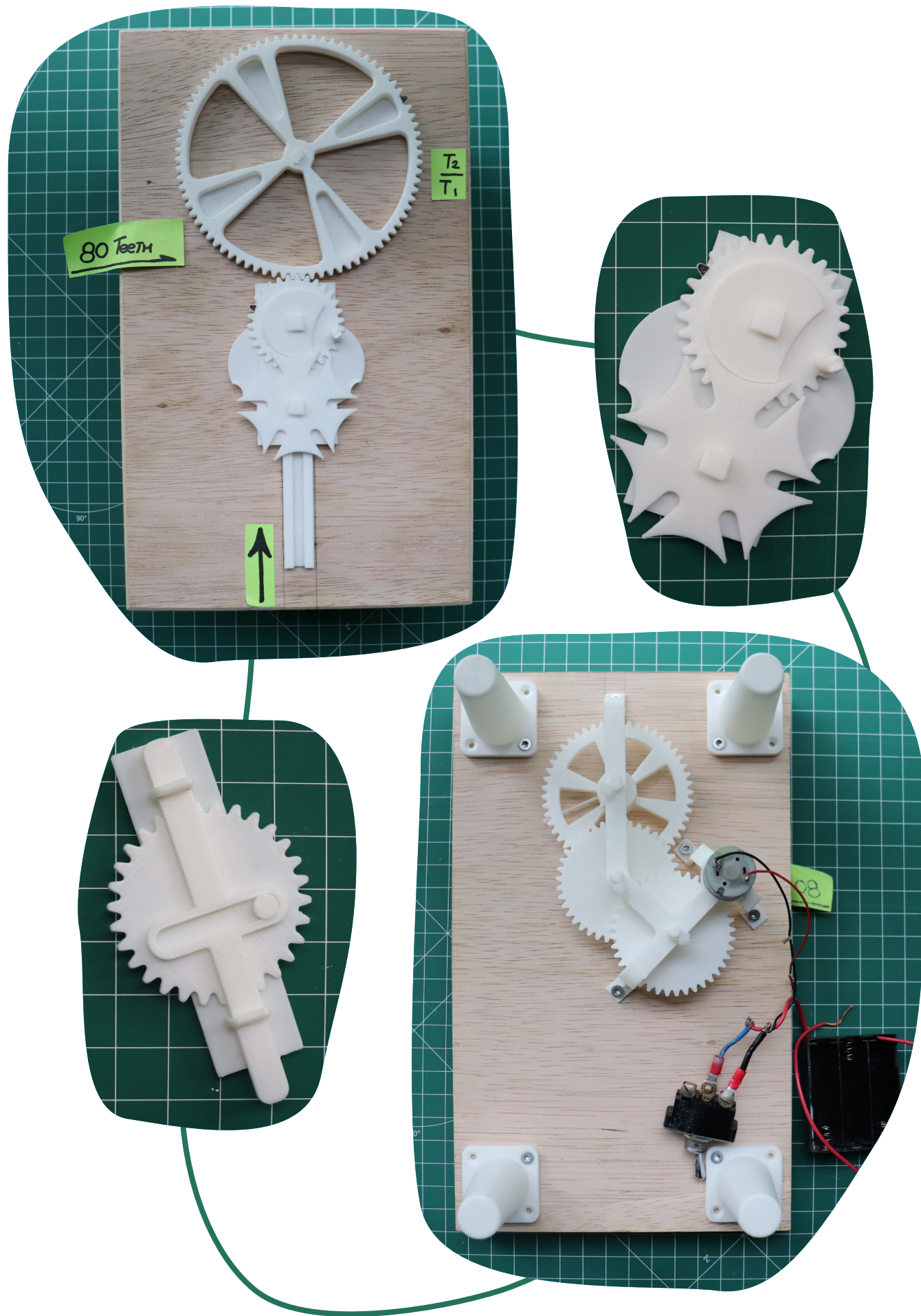


Figure 17: Mechanisms cartridge system

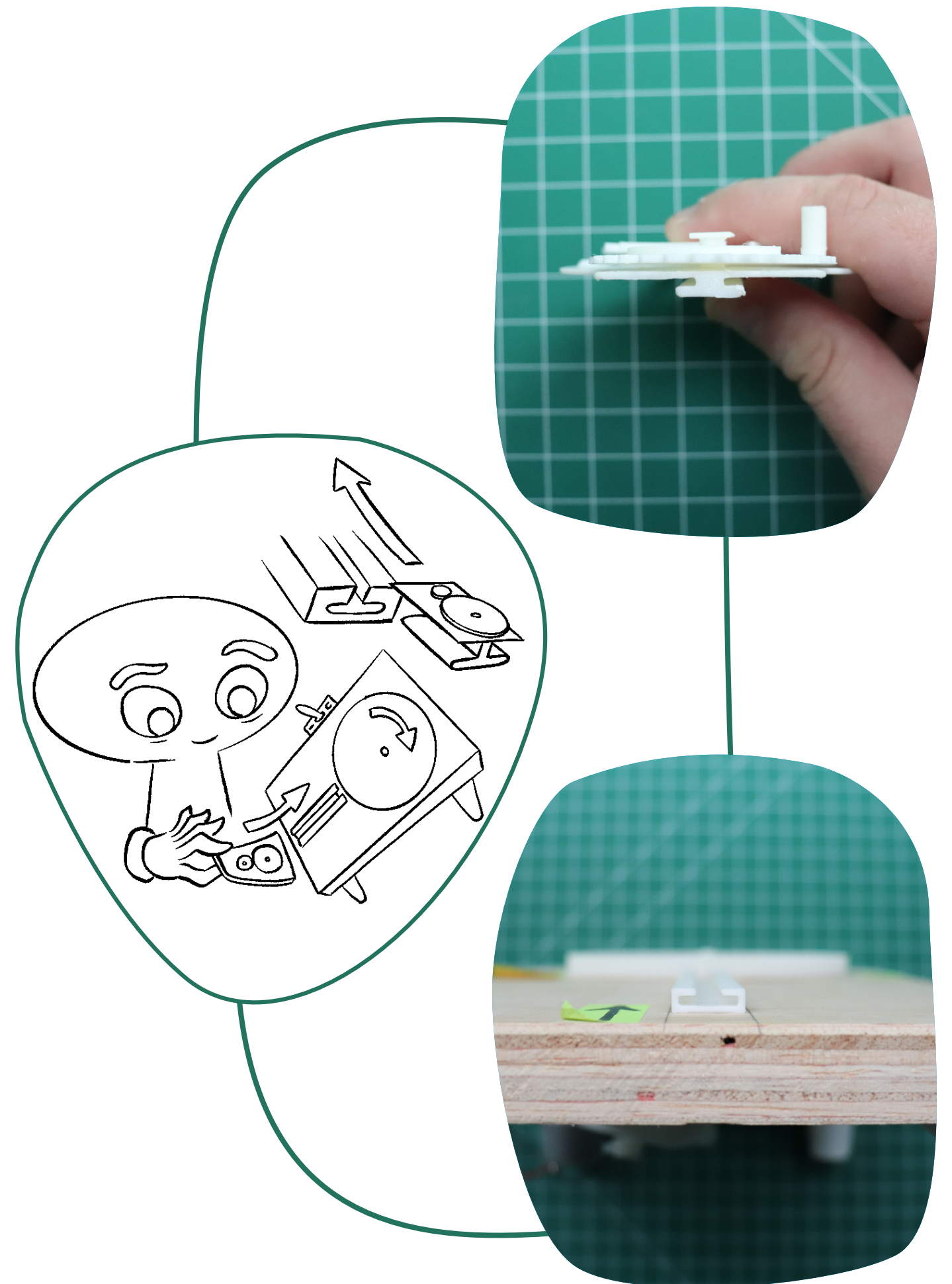


Figure 18: Mechanism cartridge system and visual representation of interaction

4.5 Prototype 05 – Mechanism on Rails

Purpose

The evaluation of the Mechanism Cartridge System demonstrated that students appreciated the increased level of interaction and experimentation. However, students also expressed a desire for greater freedom to create their own mechanical systems rather than interact with predefined mechanisms. Increasing configurability and allowing students to construct their own solutions therefore became an important design requirement for the next prototype iteration.

To address this requirement, the decision was made to continue developing the rail-based approach introduced in the previous prototype. The purpose of this prototype was to investigate whether a track system could provide students with sufficient freedom to construct and experiment with their own gear trains while maintaining ease of use and rapid iteration.

Unlike systems that rely on fixed hole patterns, a rail-based system allows components to be positioned continuously along a track. This enables students to experiment with different gear sizes, distances, and configurations without being restricted to predefined locations. The prototype therefore aimed to explore whether removing these constraints could support a more intuitive and exploratory understanding of mechanical relationships.

Prototype Description

The prototype consisted of a board containing eight cross-shaped tracks arranged around a large central gear. This configuration allowed multiple interaction points between the central drive gear and the surrounding components. The prototype can be observed in figure 19.

Sleds could be positioned along the tracks, onto which gears could be mounted. The sled and gear can be observed in figure 20. Through several rapid prototyping iterations, different rail and sled designs were developed and evaluated, based on manufacturability and usability. The goal was to create a print-in-place mechanism that could move smoothly along the track while generating sufficient friction to remain in the position chosen by the user. The resulting system allowed students to quickly adjust the position of gears and construct a wide variety of gear trains. Compared to systems based on fixed hole patterns, the prototype offered a higher degree of flexibility and supported rapid experimentation with different mechanical configurations.

It also allowed student to design and construct their own gears and add this to the system. The only variable which should be considered by the student was the module of the gear.

Evaluation

The prototype was evaluated with a group of students. This was done because research suggested that actively learning in a group resulted in a better learning experience (Johnson et al., 2014). Unlike previous prototypes, the testing approach was adapted to better suit the exploratory nature of the system. Rather than receiving specific instructions, students were given the prototype and encouraged to freely interact with it.

Participants were observed for approximately thirty minutes while experimenting with different configurations. Particular attention was paid to how students approached the construction of gear trains, how they interacted with the system, and whether the prototype encouraged experimentation and collaborative exploration.

Findings

The evaluation demonstrated that the rail-based system successfully increased the freedom available to students. Participants were able to rapidly create and modify gear trains, allowing them to experiment with a broad range of gear sizes, positions, and configurations. Compared to previous prototypes, students spent considerably more time actively constructing and testing their own ideas.

The observations suggested that the increased flexibility encouraged experimentation and exploration. Students frequently adjusted the position of gears, tested alternative configurations, and discussed the resulting behaviour with one another. This indicated that

the prototype supported a more active and hands-on learning experience than previous iterations.

At the same time, several limitations became apparent. Because the sleds could move freely within the tracks, gears occasionally shifted out of alignment during interaction. As a result, students often had to manually stabilise components to maintain proper gear engagement. This reduced the reliability of the system and occasionally interrupted the learning experience.

Although the track system provided significantly more freedom than fixed-position systems, students still experienced frustration when attempting to construct more complex configurations. The prototype increased configurability, but the movement constraints imposed by the rails continued to limit certain arrangements and interactions. The lacking amount of supporting materials such as explanation about the components or exercises were also voiced by the students. This suggested once again that students need/want some kind of guidance during the interaction.

Reflection and Design Implications

The evaluation demonstrated that increasing freedom within the system encouraged students to actively experiment with mechanical principles. Compared to previous prototypes, students spent less time observing predefined mechanisms and more time constructing, testing, and refining their own creations. This suggests that providing opportunities for open-ended experimentation can stimulate active engagement and exploration.

However, the prototype also revealed a conflict between freedom and stability. While the rail system enabled rapid experimentation, the movable sleds introduced instability that negatively affected usability. The observations indicated that students required a system that combines the flexibility to rapidly reposition components with sufficient stability to ensure reliable operation.

The findings suggest that freedom alone is not sufficient. To support meaningful experimentation, students must also be able to trust that components remain in the position they have chosen. As a result, increasing stability while maintaining flexibility became a key design requirement for the next prototype iteration.

These insights marked an important step in the development of the learning tool. The next iteration therefore focused on investigating alternative methods of positioning and securing components while preserving the freedom that students valued within the rail-based system.

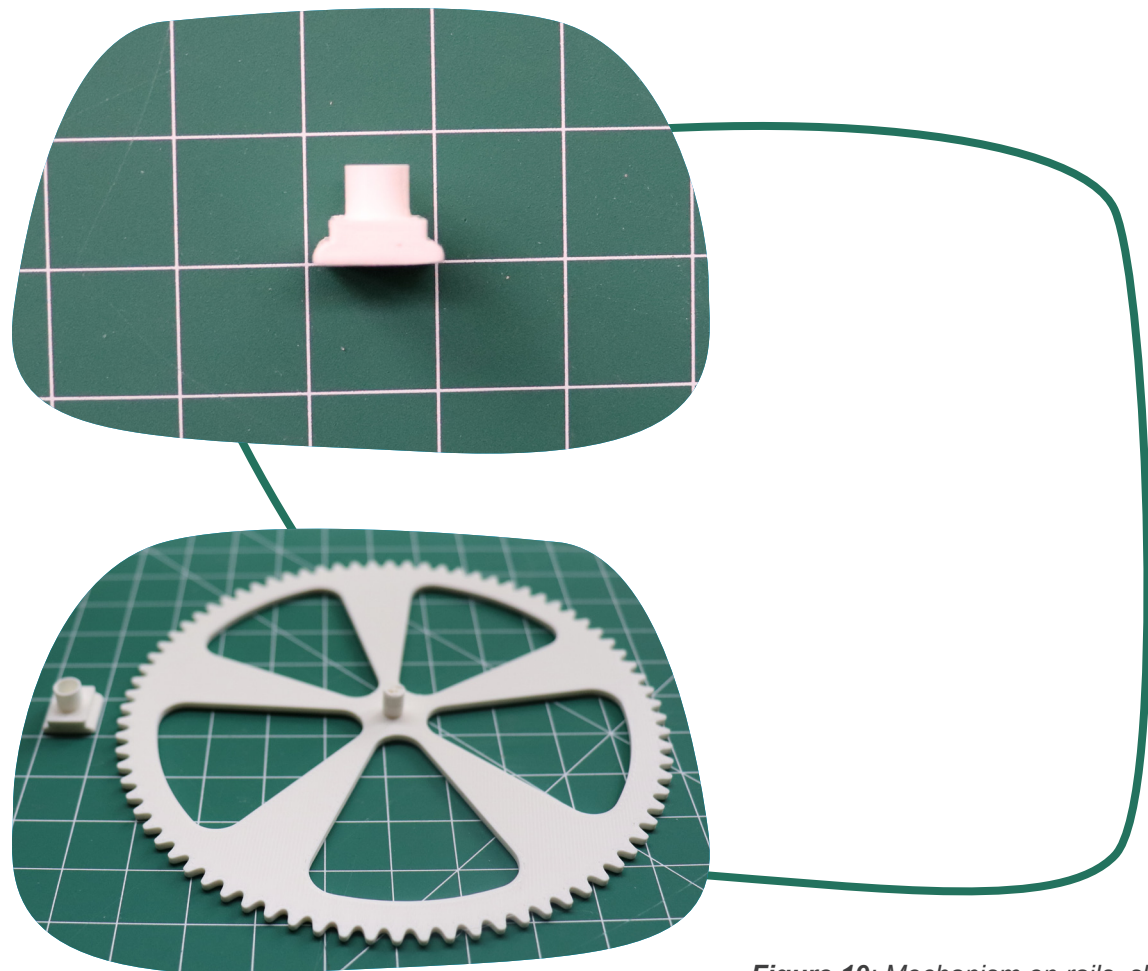


Figure 19: Mechanism on rails, sled and gear design.

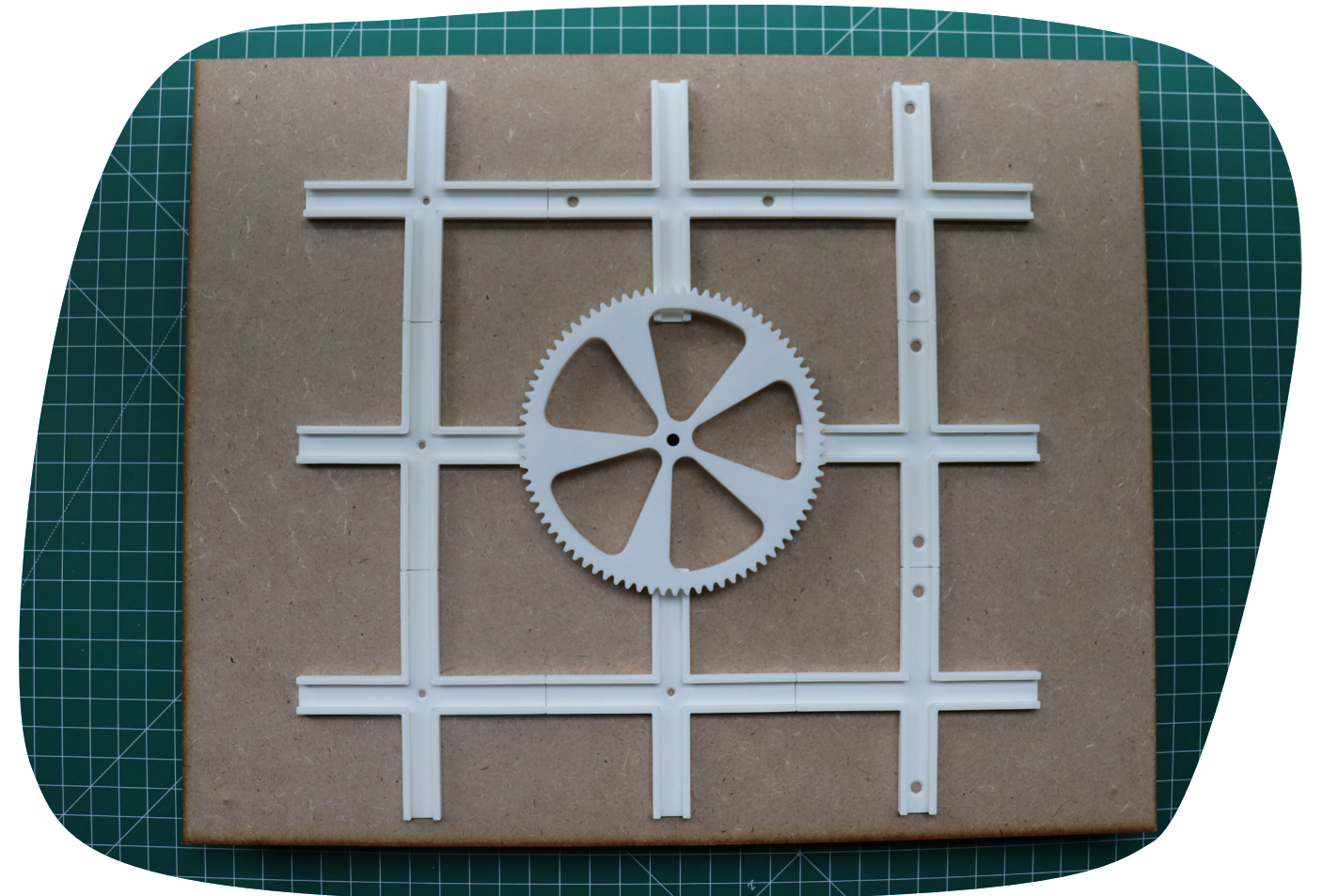


Figure 20: Mechanism on rails system and visual representation of interaction

4.6 Synthesis of Design insights

The previous prototypes generated valuable insights regarding physical interaction, construction, experimentation, and learning. While each prototype explored a different aspect of the educational challenge, several recurring themes emerged throughout their evaluation. These themes provided direction for the development of the Mechanical Garden and formed the basis of the final design requirements.

A consistent finding across the prototypes was the value of hands-on experimentation. Students were most engaged when they could actively manipulate components, test ideas, and immediately observe the effects of their actions. Prototypes that encouraged exploration and iterative problem-solving generally generated more discussion and engagement than solutions focused primarily on information transfer.

A second recurring insight was the importance of construction freedom. Participants appreciated the ability to create and modify their own solutions rather than following predetermined configurations. However, the evaluations also demonstrated that freedom alone was insufficient. Without educational guidance, some participants were unsure how to approach the learning objectives or which concepts they were expected to explore. This highlighted the importance of balancing open-ended experimentation with structured educational support.

Furthermore, several prototypes demonstrated the importance of immediate visual feedback. Students were better able to understand mechanical principles

when the consequences of their design decisions became directly visible through movement. Observing the behaviour of gears, linkages, and other mechanisms helped participants connect theoretical concepts to physical outcomes.

Collaborative interaction also emerged repeatedly throughout the testing of the mechanisms on rails prototype. Participants frequently discussed ideas, shared observations, and jointly explored solutions. Since cooperative learning has been shown to positively influence learning outcomes (Johnson et al., 2014), supporting collaboration became an important consideration in the development of the final learning tool.

Finally, the evaluations highlighted the importance of technical reliability. Components that detached, shifted, or behaved unpredictably interrupted the learning process and reduced opportunities for experimentation. The final system therefore needed to provide a stable environment while maintaining the flexibility required for exploration and prototyping.

Based on these insights, the following design requirements were formulated for the development of the Mechanical Garden:



The tool must support repeated experimentation and iteration.

The tool must allow students to construct and modify their own mechanisms.

The tool must provide structured educational guidance alongside opportunities for exploration.

The tool must support collaboration between multiple students.

The tool must provide sufficient freedom for students to explore independently.

The tool must provide a stable and reliable environment for experimentation.

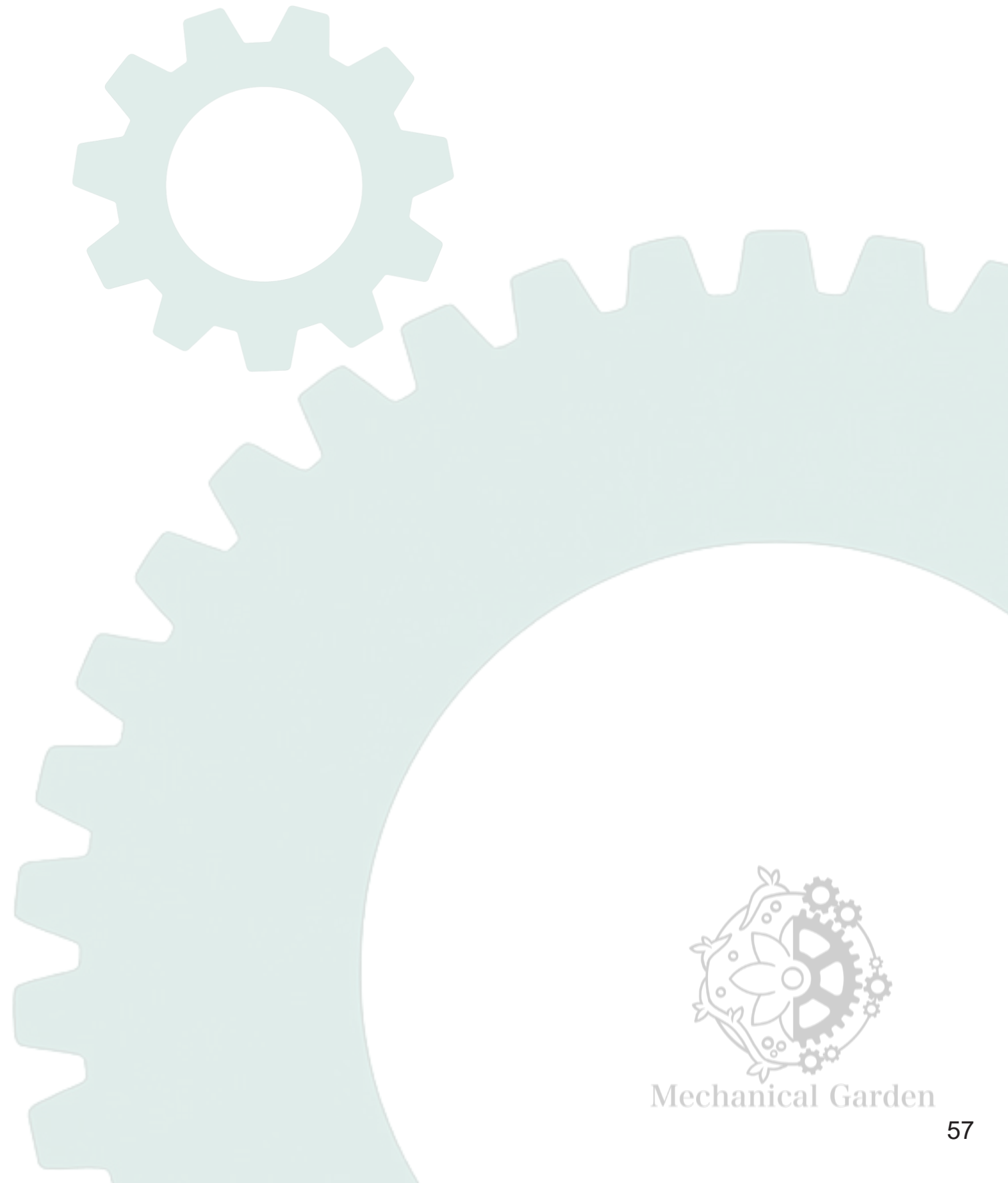
The tool must provide immediate visual feedback regarding the behaviour of mechanisms.

These requirements formed the foundation for the development of the Mechanical Garden presented in the following sections.

Chapter 5.

Iterations towards final design

Multiple design iterations were conducted to further develop and refine the learning tool. This chapter presents the evolution of the Mechanical Garden and its individual components. Through prototyping, testing, and evaluation, design improvements were identified and implemented to enhance functionality, usability, manufacturability, and educational value. The chapter demonstrates these iterations ultimately resulted in the final design.



5.1 Development of the Mechanical Garden

After synthesizing the insights generated from the previous prototypes, a clear design direction emerged. The focus of the project shifted from exploring educational opportunities towards the development and refinement of a dedicated learning system centred around mechanical movement. The aim of this system was to support Bachelor Industrial Design Engineering students in developing a better understanding of mechanical principles, experimenting with mechanical systems, and designing their own mechanical solutions within the context of the course DP3.

The Mechanical Garden was envisioned as a direct successor to the track-based systems developed during the Mechanism Cartridge and Mechanisms on Rails prototypes. These prototypes demonstrated the educational value of allowing students to construct and experiment with their own mechanical configurations. However, the evaluations also revealed several limitations. Although the rail system provided freedom in positioning components, it proved difficult to maintain stability during use. Components could shift unintentionally, causing gears to lose alignment and reducing the reliability of the system.

Several iterations of the rail-based concept were explored to address these issues. However, it became apparent that the limitations were inherent to the concept itself rather than the result of specific design details. As a result, a different approach was investigated.

The new concept replaced the rail system with a magnetic building system. By using magnetic force as the primary method of attachment, components could be positioned freely across the build plate while remaining securely fixed during interaction.

This approach combined the flexibility valued by students with the stability required for reliable experimentation and observation. In addition, magnetic connections allowed components to be repositioned without tools, supporting the rapid experimentation that emerged as a key requirement throughout the earlier prototype iterations.

The magnetic system represented the first iteration in which the identified educational, functional, and usability requirements could be addressed simultaneously, forming the foundation of the Mechanical Garden learning system.

Manufacturing method prototypes

Unless stated otherwise, all Mechanical Garden components were designed in Fusion-360, as print-in-place parts manufactured from PLA using FDM 3D printing. This approach made rapid prototyping possible, supplied more freedom during the design process, allowed for complex structures to be designed and minimised waste (Ngo et al., 2018).

The following sections describe the evolution of the individual Mechanical Garden subsystems and the design decisions that ultimately resulted in the final learning tool.



Evolution of the Mechanical Garden

Throughout the design process, the Mechanical Garden evolved from a physical construction tool focused primarily on experimentation into a more comprehensive educational system combining experimentation, instruction, and creation. This expansion was driven by findings from earlier prototype evaluations, which showed that freedom of interaction alone was not sufficient. Students also required guidance, structure, and opportunities to create custom components.

As a result, the scope of the project expanded beyond the physical prototype itself. The final concept consists of three interconnected elements: the Mechanical Garden, a Magnetic modular construction

system, an accompanying exercise booklet, and a parametric gear designer. The exercise booklet provides structure and guidance during the learning process, while the parametric gear designer enables students to create custom gears that can be integrated directly into the system. Together, these elements support a balance between guided learning and open-ended experimentation.

The following visualisations present the overall evolution of the Mechanical Garden concept, from the first prototype to the final version (Figure 21). Detailed discussions of the individual subsystems and their development are provided in the subsequent sections of this chapter.

The Mechanical Garden consists of several interconnected subsystems that together support experimentation with mechanical movement. The following sections discuss the development of these subsystems and the iterative process through which they evolved. Rather than documenting every prototype produced during the project, the focus is placed on iterations that generated meaningful findings and directly informed the final design. For each subsystem, the most relevant design decisions, observations, and resulting refinements are presented.

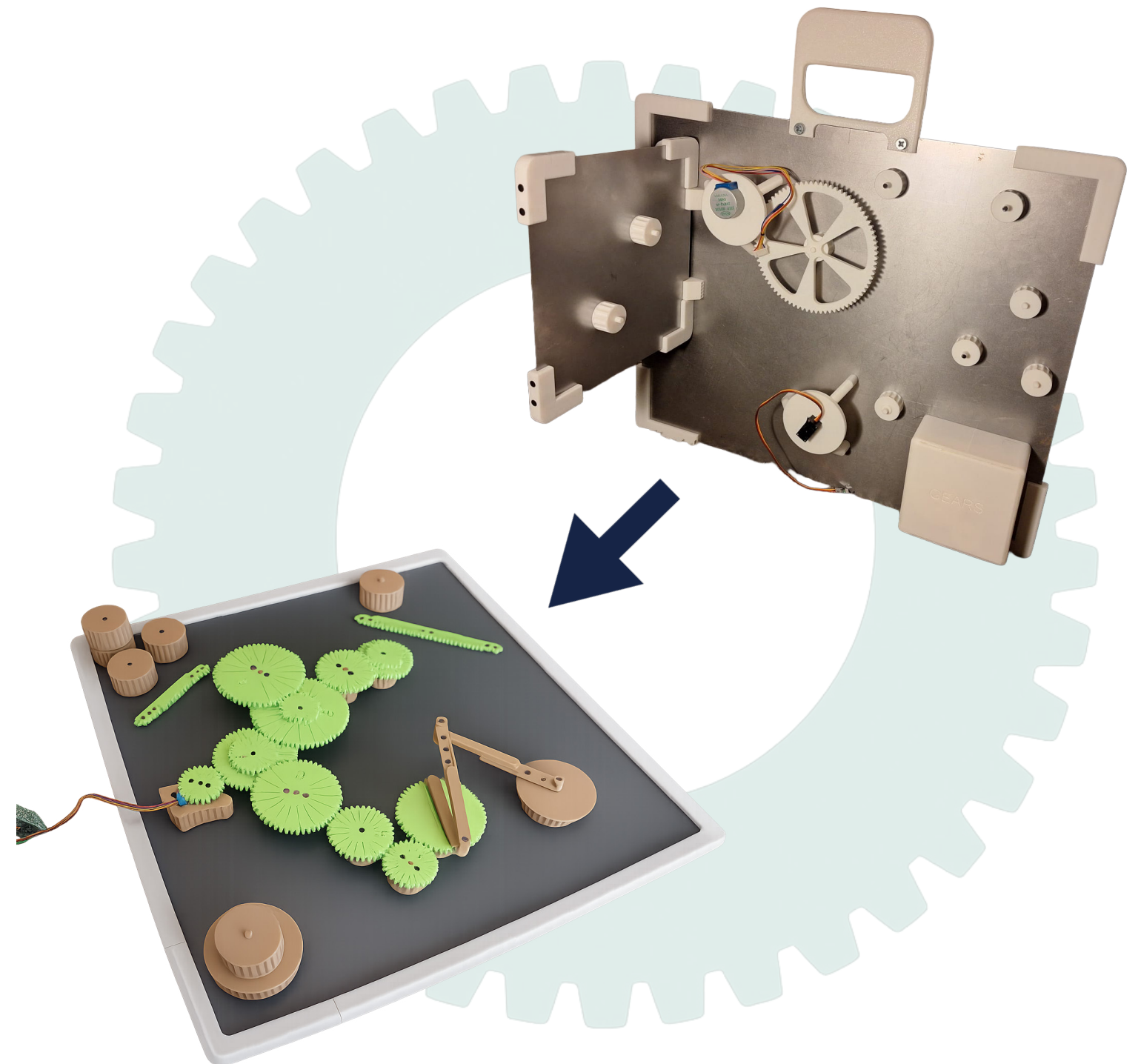


Figure 21: Overall evolution of the Mechanical Garden learning tool.

5.2 The building plate

This Chapter describes all iterations, designs and findings of the magnetic building plate (Figure 22).



Figure 22: All prototypes of the building plate component of the Mechanical Garden

5.2.1 Building plate 01

Design

The first building plate consisted of an untreated sheet of steel measuring 300 × 600 × 0.8 mm. Steel was selected because of its magnetic properties, structural strength, and availability. The plate provided a surface onto which the magnetic components of the Mechanical Garden could be freely positioned.

Findings

Testing showed that the building plate successfully supported the magnetic construction system. Students were able to place, reposition, and remove components without difficulty. However, several limitations became apparent during use.

First, the untreated steel surface showed signs of corrosion over time due to exposure to moisture, oils, and acids present in the environment and on users' hands. Secondly, the dimensions of the plate proved insufficient for collaborative use. While the surface provided adequate space for a single user, observations during testing sessions with multiple students revealed that larger constructions quickly occupied the available area. Students frequently had to reach across the board to interact with components, occasionally disturbing existing mechanisms.

5.2.2 Building plate 02

Final design

To address these findings, research was conducted into ergonomic reach distances and the dimensions of collaborative work surfaces Appendix C. Ergonomic studies indicate that the optimal seated reach zone is approximately 400 mm (Bosch Rexroth, 2014)., while anthropometric data from Dined shows an average reach distance of approximately 505 mm for Dutch students (DINED, n.d.). In addition, an analysis of the best selling four-player board games revealed average board dimensions of approximately 507 × 507 mm (The Best-Selling Board Games Of All Time, Ranked, n.d.),

Based on these findings, the dimensions of the building plate were revised to 500 × 500 mm. The larger, more square format improved accessibility for multiple users positioned around the system while simultaneously providing additional space for the construction of larger mechanical assemblies. These modifications addressed both the ergonomic and collaborative limitations identified during testing of the previous iteration. In addition, the steel plate was powder-coated to improve durability and prevent corrosion during long-term use.

5.3 Building plate border

The building plate border was designed to fit around the 0.8 mm thick steel building plate (Figure 23-24). The border serves multiple functions within the Mechanical Garden.

First, it covers the sharp edges of the steel plate, improving user safety during interaction. Second, it acts as a physical barrier that reduces the likelihood of components rolling or sliding off the building plate during use. Finally, the border incorporates features that allow multiple building plates to be stacked, improving storage and transportation of the system.

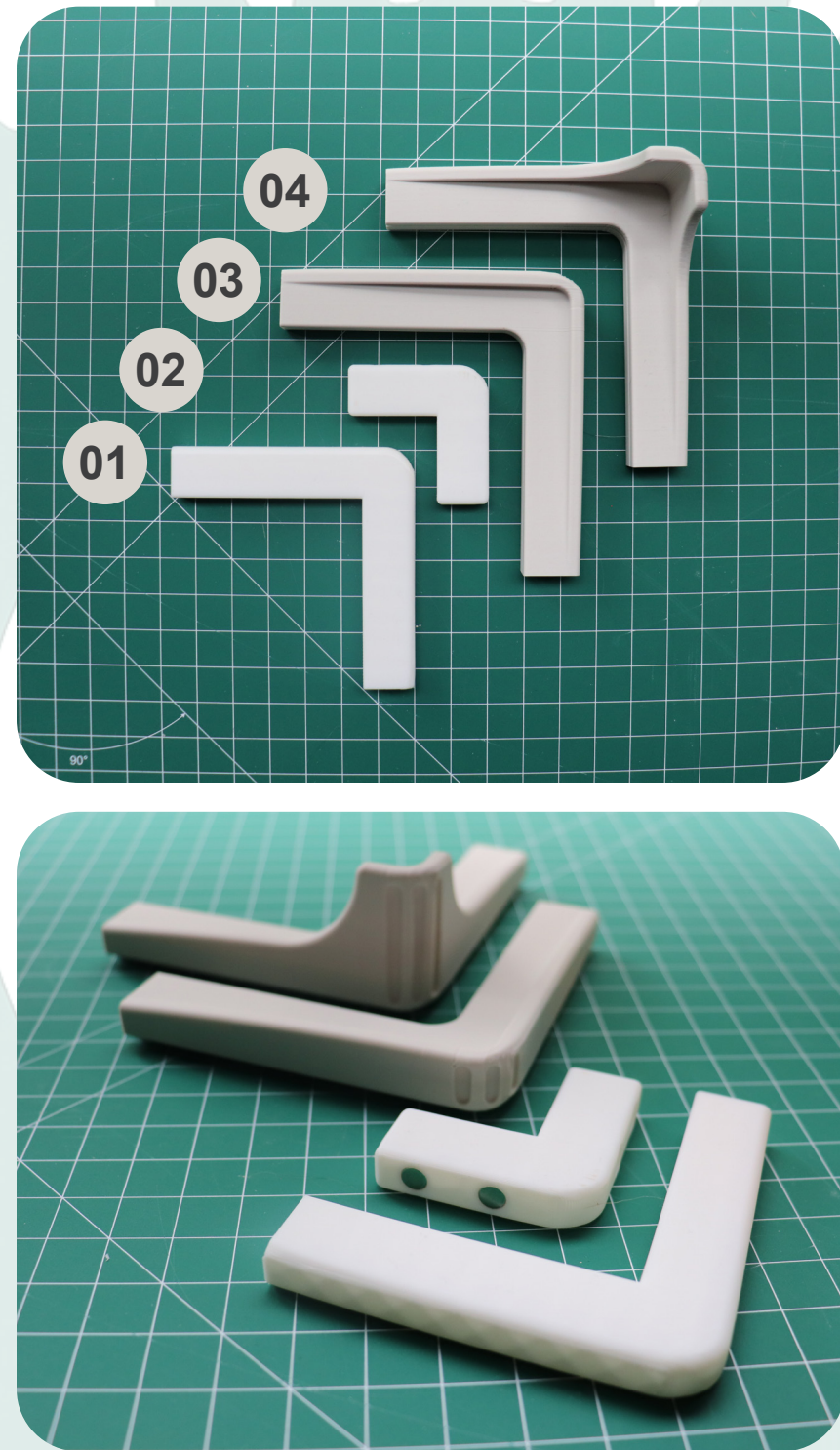


Figure 23: All prototypes of the building plate border component of the Mechanical Garden

5.3.1 Building plate border 01

Design

The first border design consisted of a 3D-printed PLA component intended to cover the corners of the steel building plate. The design featured a simple rounded geometry that could be easily attached to the plate while protecting users from the sharp metal corners.

Findings

The corner components functioned as intended and successfully reduced the risk

of users encountering the sharp corners of the steel building plate. However, the edges between the corner components remained exposed. During testing, this occasionally resulted in negative user experiences when participants encountered the unprotected steel edges. These findings indicated that protection of the corners alone was insufficient and that a solution covering the entire perimeter of the building plate was required.

5.3.2 Building plate border 02

Design

This iteration explored a suggestion provided during an interview with an educator. The suggestion proposed integrating magnets into the corners of the building plate, allowing multiple Mechanical Garden boards to be connected and thereby increasing the available construction area. To accommodate this functionality, the geometry of the previous corner design was modified to incorporate magnetic connection points while maintaining its protective function.

Findings

This iteration did not address the primary limitation identified in the previous design, namely the exposed edges between the corner components. However, it provided an opportunity to evaluate the potential benefits of connecting multiple building plates. Although the concept proved technically feasible, later stages of the design process indicated that increasing the dimensions of a single building plate was a simpler and more practical solution.

Figure 24: All prototypes of the building plate border component of the Mechanical Garden



5.3.3 Building plate border 03

Design

This design extended the length of the corner and added long straight pieces which were able to bridge the gap between the corners. The design was optimised to follow the design language of the whole project and an experimentation with a nesting system was designed in this iteration.

Findings

This iteration successfully addressed several shortcomings identified in the previous designs. The border covered the entire perimeter of the building plate, eliminating exposure to sharp steel edges. In addition, the integrated nesting system functioned as intended, allowing multiple

building plates to be stacked securely for storage and transportation. However, testing revealed that the clearance provided by the nesting system was insufficient to accommodate components attached to the building plate. As a result, building plates could only be stacked when all components had first been removed. Later in the design process, it was determined that allowing components to remain attached to the building plate would significantly simplify setup, storage, and cleanup procedures. Consequently, the nesting system required further refinement to provide sufficient space for attached components while maintaining its stacking functionality.

5.3.4 Building plate border 04

Final design

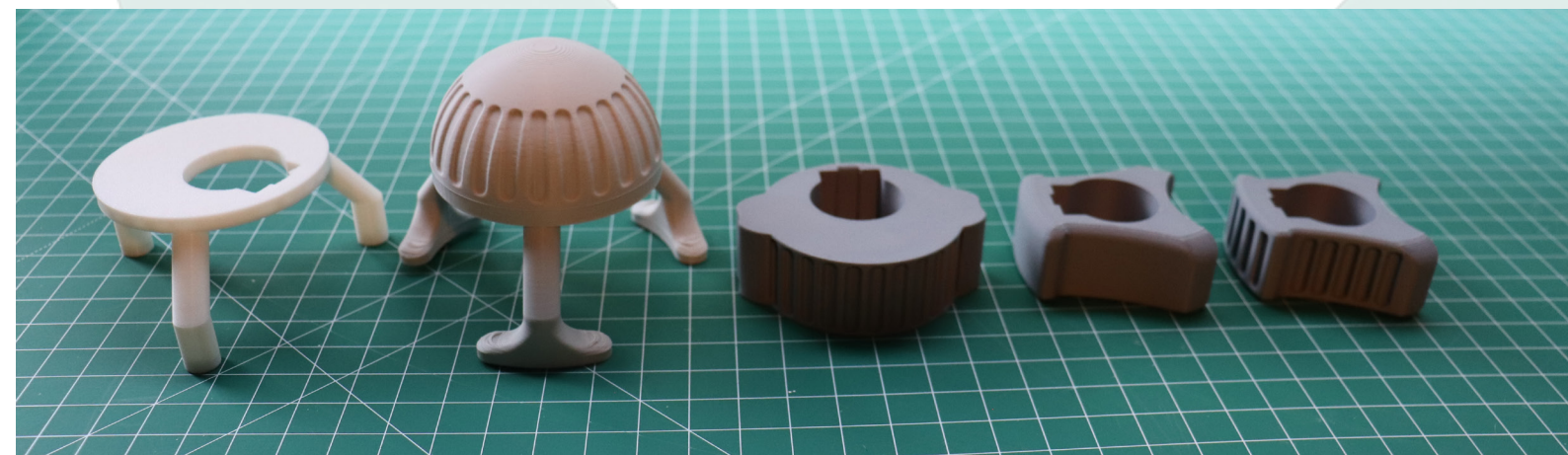
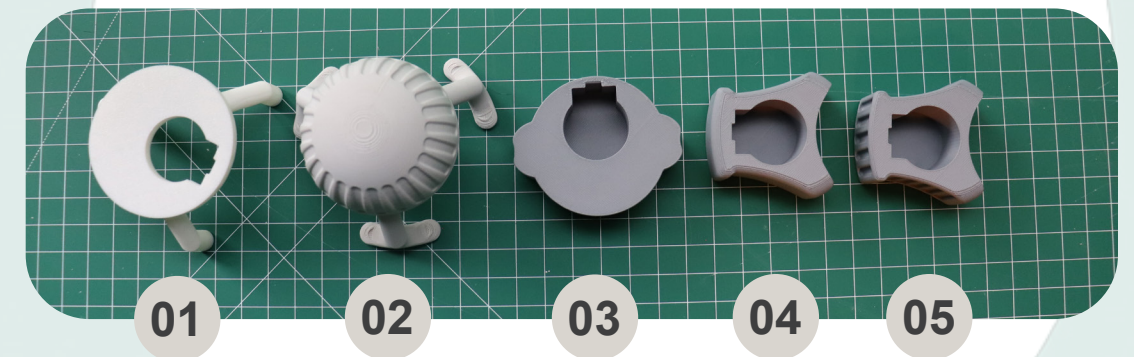
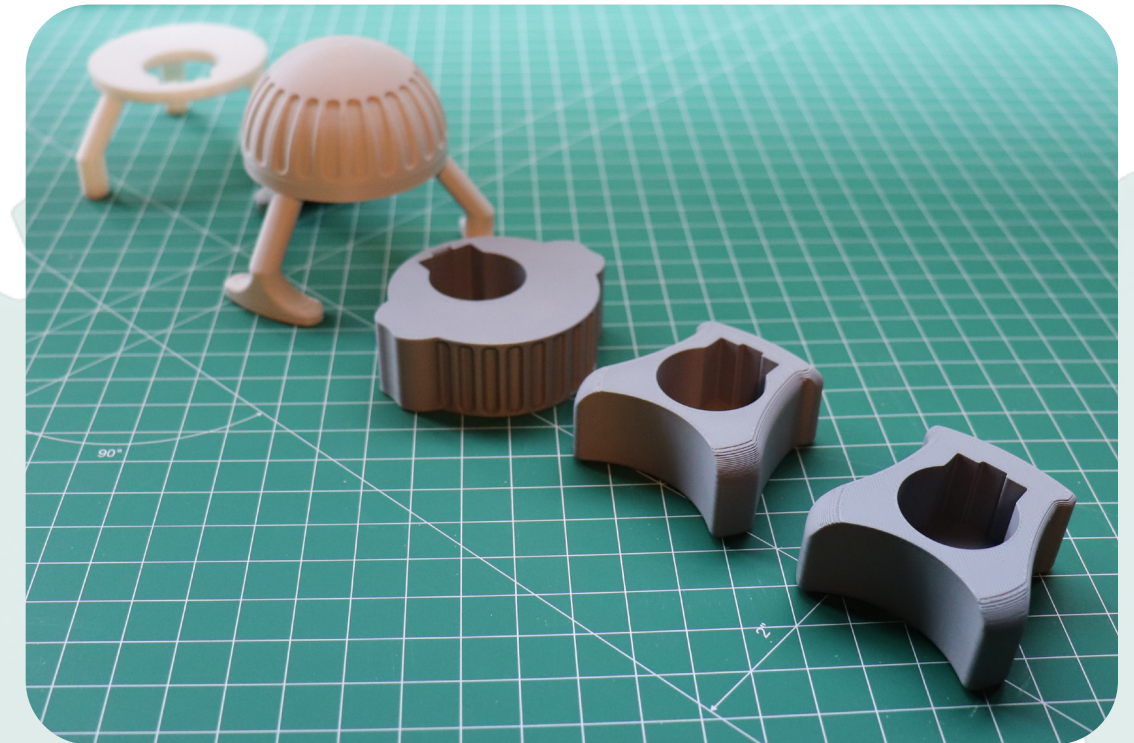
The final border design refined the nesting system, making it possible to stack multiple building plates while leaving components attached to the surface. This significantly reduced setup and cleanup time. In addition, the final iteration incorporated the established design language of the Mechanical Garden,

resulting in a more visually coherent appearance. The geometry of the border was further optimized for manufacturing. The design was developed as a print-in-place component that can be produced without support structures. This improved accessibility and reproducibility of the design.

5.4 Motor mount

The motor mount forms the interface between the drive system and the components of the Mechanical Garden. By positioning the stepper motor in the motor mount and placing a gear on the drive shaft of the motor, the components are able to transfer rotational movement to the gears and mechanisms constructed by students. Throughout the design process, several iterations were developed to improve stability, reliability, ergonomics, and visual integration within the overall system (Figure 25).

Figure 25: All prototypes of the Motor mount component of the Mechanical Garden



5.4.1 Motor mount 01

Design

The first motor mount was designed to support the stepper motor in an inverted orientation, enabling the motor assembly to be positioned freely across the building plate.

Findings

Testing revealed that the holding force of the motor mount was insufficient. Under increased loads, the mount could shift position, reducing the reliability of the

system and hindering observation of the mechanisms. Furthermore, participants perceived the visual appearance of the motor mount as inconsistent with the overall design language of the Mechanical Garden. An additional issue was identified with the inverted motor configuration. Although infrequent, the gear attached to the motor shaft occasionally detached during operation, resulting in temporary interruptions of the mechanism's movement.

5.4.2 Motor mount 02

Design

To address the stability issues observed in the first iteration, the motor mount was redesigned to accommodate a larger number of magnets. In addition, a dome-shaped cover was developed and magnetically attached to the top of the assembly. The cover was intended to conceal the stepper motor and better align the motor mount with the overall design language of the Mechanical Garden.

Findings

Testing showed that the additional magnets significantly increased the holding force of the motor mount. As

a result, the assembly remained more stable during operation and was less prone to shifting when higher forces were applied. Furthermore, the dome-shaped cover improved the visual integration of the motor mount within the overall system and reduced the visibility of the electronic components. However, because the stepper motor was mounted in an inverted orientation, the gear attached to the motor shaft was prone to detachment during operation. This reduced the reliability of the system and occasionally interrupted the movement of the mechanisms being tested.

5.4.3 Motor mount 03

Design

For the third motor mount iteration, the stepper motor was rotated by 90 degrees to improve the reliability of the drive system. To accommodate both the motor and the integrated magnetic connection system, the height of the mount was increased. The resulting assembly consisted of a 22 mm motor section combined with a 4 mm magnetic interface. From this point forward other components in the system had to be adapted to this size so gears were able to interact with each other. Despite these modifications, the motor mount retained the design language established throughout the Mechanical Garden.

Findings

The redesigned motor mount successfully prevented the drive gear from detaching

from the stepper motor during operation, thereby improving the reliability of the system. Participants also reported that the exposed position of the drive gear improved visibility, making it easier to construct and analyse larger gear trains. Furthermore, the magnetic connection between the motor mount and the building plate continued to provide sufficient holding force during use.

However, several limitations remained. The ergonomics of the motor mount were found to be suboptimal, particularly when repositioning the assembly on the building plate. In addition, the circular geometry of the mount limited the placement of smaller gears around the drive gear, reducing the range of possible gear configurations that could be constructed.

5.4.4 Motor mount 04

Design

The final motor mount integrated the findings from the previous iterations into a design that fully supports the intended functionality of the Mechanical Garden. The revised geometry allows gears of all sizes to engage with the drive gear, increasing the range of possible gear configurations that can be constructed. In addition, the updated form improved the ergonomics of the assembly, making it

easier to position, remove, and reposition the motor mount with greater accuracy. Despite these modifications, the motor mount retained the established design language of the Mechanical Garden, ensuring visual consistency throughout the system. The geometry of the final motor mount was further optimised for manufacturability, allowing the component to be produced without support structures.

5.4.5 Motor mount 05

Final design

The final motor mount is motor mount 04, but the design of the ridges that are used throughout the Mechanical Garden has been implemented as well. Making it more coherent with the rest of the tool and also increasing grip on the motor mount.

5.5 Gears

Throughout the project, numerous gear variations were developed and tested (Figure 26-27). These included solid gears, gears with spoke structures, and gears incorporating labels or numbers to indicate the number of teeth and improve the observation of rotational movement.

All gears within the Mechanical Garden were designed around a module of 1.5. The module is a parameter that defines the size of the gear teeth and determines whether gears can properly mesh with one another. By standardising the module throughout the system, gears of different sizes could be freely combined while maintaining compatibility.

As the project progressed, it became apparent that manually designing gears in CAD software could present a barrier for students. Consequently, the focus shifted from developing individual gear variants towards creating a parametric gear designer. This tool enables students to quickly generate custom gears that are directly compatible with the Mechanical Garden.

The parametric gear designer ultimately became the primary method for creating gears within the Mechanical Garden and forms the basis of the final gear system. The iterations of the parametric gear designer are discussed in the following section.

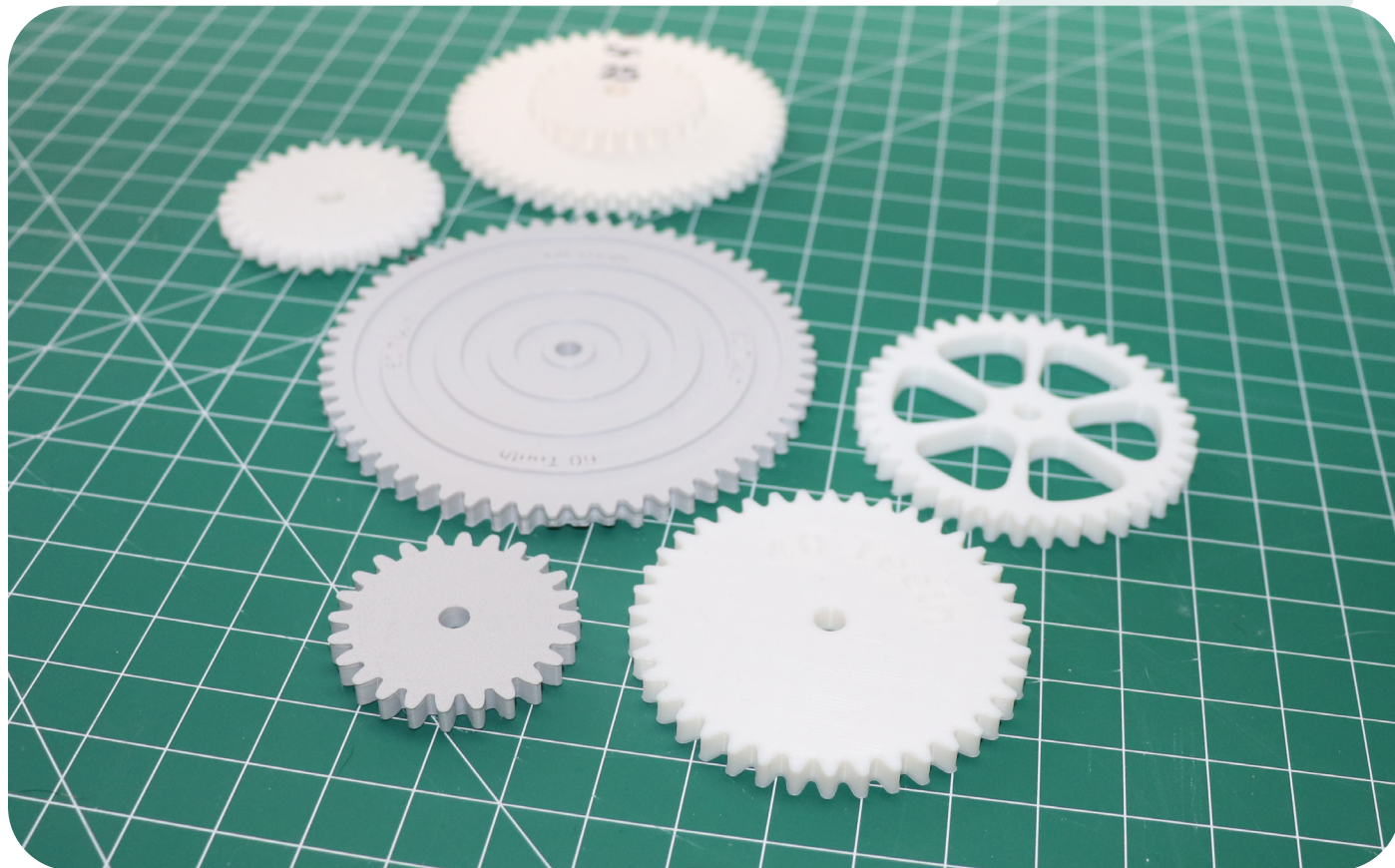


Figure 26: All prototypes of the Gear component of the Mechanical Garden

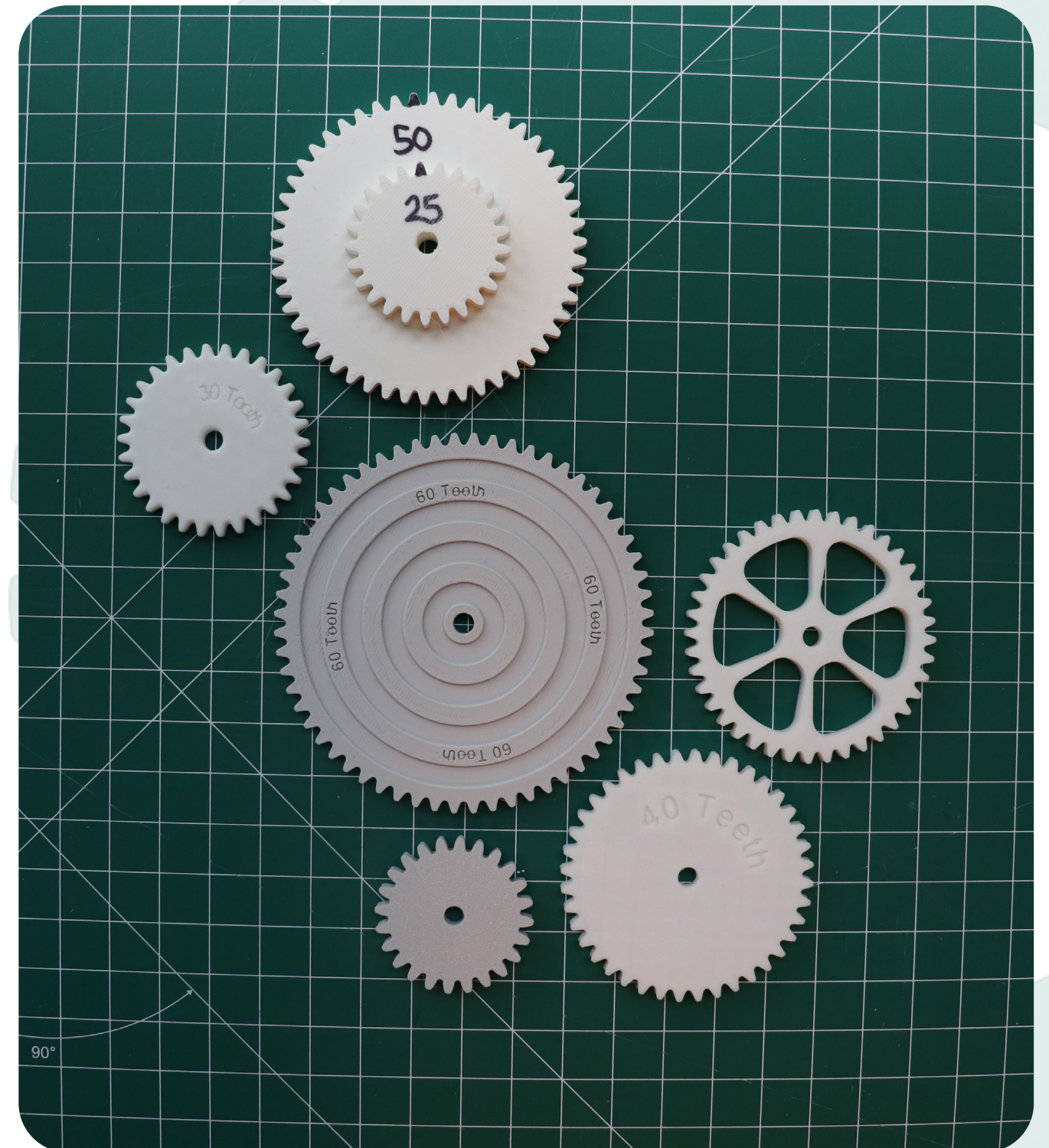


Figure 27: All prototypes of the Gear component of the Mechanical Garden

5.6 Magnetic parametric gears

As discussed in the previous section, a parametric gear designer was developed to enable students to design and manufacture custom gears compatible with the Mechanical Garden. Throughout the project, the design of the parametric gears evolved through multiple iterations in response to insights gained from testing and use (Figure 28).

The parametric gear designer allows students to adjust two primary variables: the number of teeth and the module of the gear. Although the module can be adjusted, a value of 1.5 was selected as the standard throughout the Mechanical Garden system. This value was chosen because it produced gears that were large enough for students to interact with while still fitting within the build volume of commonly available 3D printers.

The following sections discuss the evolution of the parametric gear design and the decisions that led to the final version.

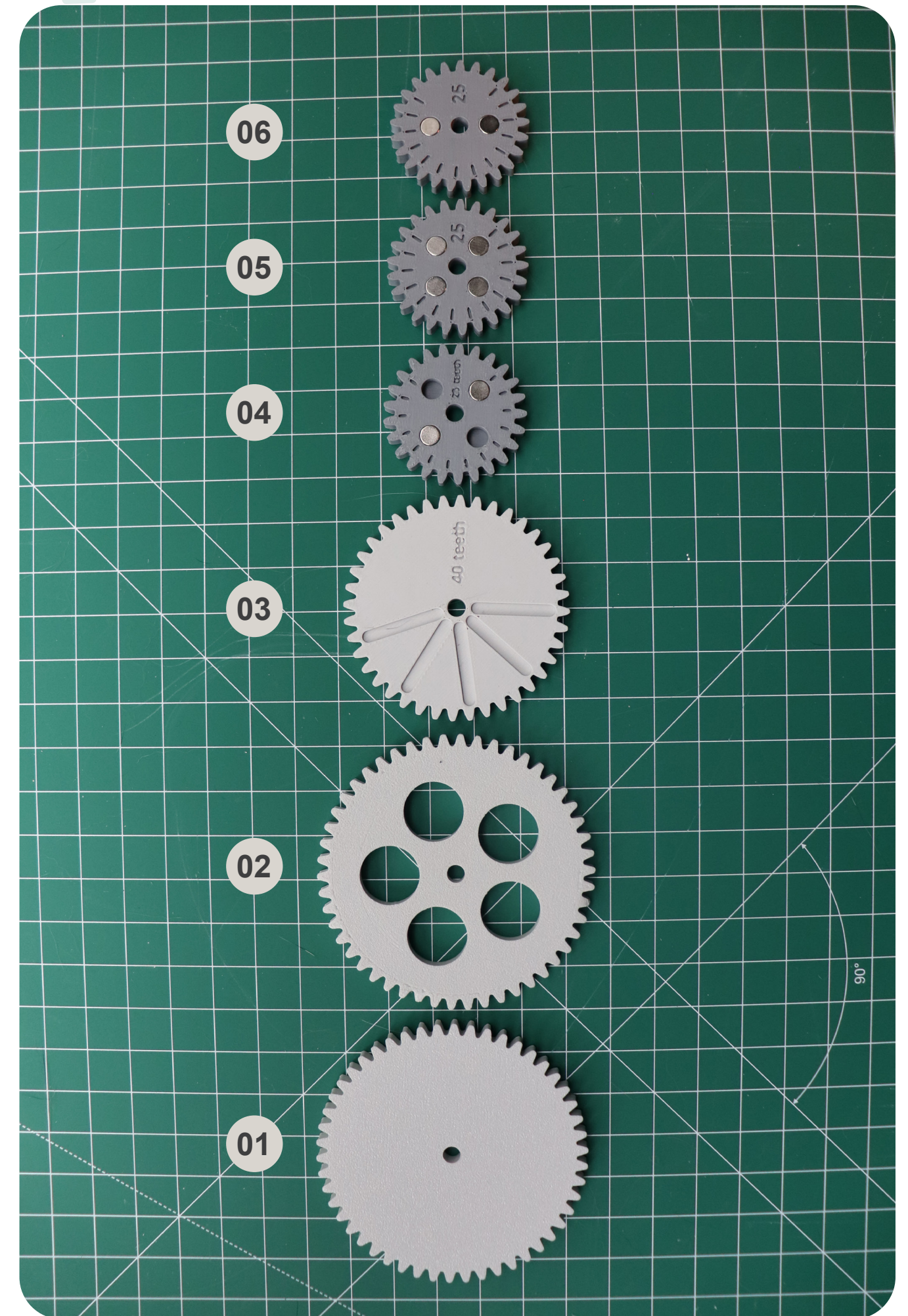


Figure 28: All prototypes of the Parametric Gear component of the Mechanical Garden

5.6.1 Magnetic parametric gear 01

Design

This first iteration consisted out of a simple solid spur gear design. No spokes, text or material saving aspects were integrated in this version.

Findings

The gear functioned as intended and was fully compatible with the existing gear system and gear mounts of the Mechanical Garden. However, participants indicated that the gear provided limited information regarding its dimensions and number of teeth. In addition, several students suggested the inclusion of a visual marker on the gear to make rotational movement easier to observe and to facilitate counting the number of rotations over a given period.

single parametric gear system capable of supporting both standard and compound gear configurations would provide greater flexibility and better align with the educational goals of the Mechanical Garden.

5.6.2 Magnetic parametric gear 02

Design

This iteration introduced openings within the body of the gear to reduce material consumption during manufacturing while maintaining the overall dimensions and functionality of the gear.

Findings

The gear functioned as intended and remained fully compatible with the other gears in the Mechanical Garden system. Although the openings reduced material usage, they introduced a new limitation. During testing, the edges of the openings occasionally caught on the gear mounts, causing increased friction and, in some cases, preventing the mechanism from rotating smoothly.

5.6.3 Magnetic parametric gear 03

Design

This iteration replaced the openings in the gear with engraved slots. This approach reduced material usage while eliminating the risk of the gear catching on surrounding components. In addition, the ridges allowed the established design language of the Mechanical Garden to be incorporated into the gear design. To improve usability, the number of teeth was embossed directly onto the gear, enabling students to easily identify and compare gears during use.

Findings

This iteration successfully addressed the limitations identified in the previous version. The gears functioned reliably and the embossed tooth count improved their educational value. In parallel with this development, a parametric compound gear system was also explored. However, testing revealed that pre-manufactured compound gears reduced opportunities for experimentation and limited the freedom students had to create their own solutions. These findings suggested that a

5.6.4 Magnetic parametric gear 04

Design

This iteration focused on enabling the creation of compound gear systems using individual gears. Several solutions were explored, including permanently joining gears through adhesive bonding, introducing a dedicated axle system with locking mechanisms, and designing interlocking geometries that would allow gears to mechanically connect. Ultimately, a magnetic connection system was selected.

Four holes were integrated into the parametric gear design to accommodate neodymium magnets. By implementing the same feature across all gears, individual gears could be magnetically connected to form compound gear systems. Careful attention was required during assembly, as the orientation of the magnetic poles determined whether gears would attract or repel one another.

Findings

The magnetic connection system performed well and successfully enabled the creation of compound gear configurations while maintaining flexibility and ease of use. However, the integration of the magnet holes reduced the available space for embossed information, making the tooth count more difficult to read. In addition, the strength of the magnets occasionally caused issues during assembly. When gears related to identical magnetic poles facing one another, magnetic repulsion could cause the gears to detach from the gear mount.

5.6.5 Magnetic parametric gear 05

Design

This iteration built upon the previous magnetic parametric gear design. To improve readability, the embossed word “teeth” was removed, leaving only the numerical tooth count displayed on the gear. This provided more space for the number and improved its visibility.

Findings

The revised design improved the readability of the tooth count and made gear identification easier during use. However, testing revealed that the number of integrated magnets remained excessive. The resulting magnetic forces were stronger than required, occasionally causing unwanted interactions between gears and reducing the ease of assembly.

5.6.6 Magnetic parametric gear 06

Final Design

This iteration reduced the number of integrated magnets from four to two while retaining the embossed tooth count and engraved ridges. The reduction in magnetic force improved ease of assembly while maintaining the functionality of the magnetic compound gear system.

correctly during assembly. To simplify this process, gears were produced as matched pairs with complementary magnetic orientations.

The evolution of the parametric gear system demonstrates a shift from optimizing individual gear designs towards enabling greater flexibility and customization for students. The resulting system allows students to generate gears that are compatible with the Mechanical Garden while maintaining opportunities for experimentation and exploration.

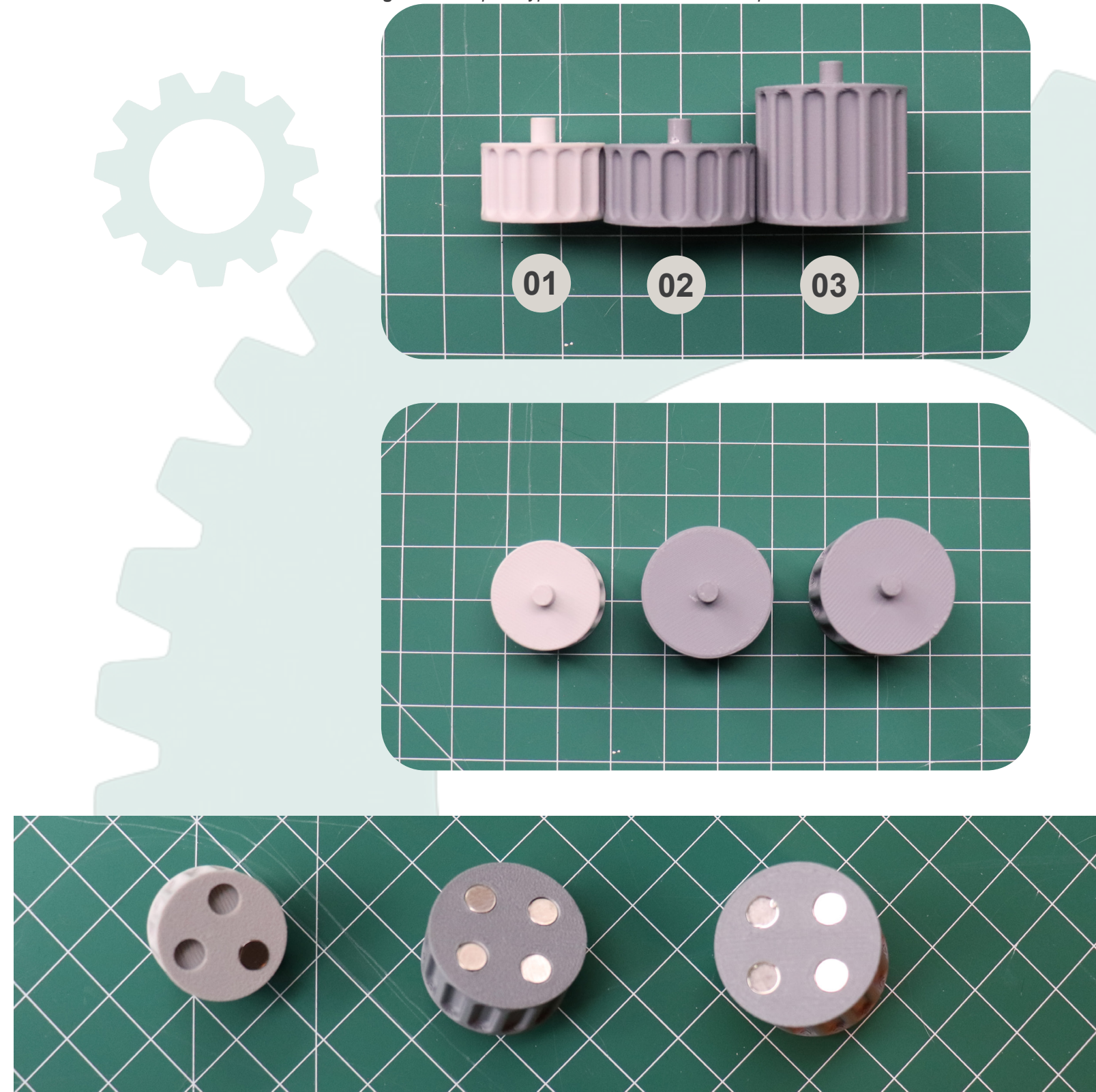
Testing showed that the gears could be reliably combined to form compound gear configurations and that unwanted magnetic interactions were significantly reduced. The only remaining limitation was the need to align magnetic polarities

5.7 Gear mounting base

The gear mounting base functions as the interface between the gears and the building plate, allowing gears to be positioned and rotated within the Mechanical Garden (Figure 29).

The height of the mounting base was designed to ensure proper meshing between mounted gears and the drive gear attached to the stepper motor. In addition, the mounting base was shaped to be comfortable to grasp and reposition during use. The established design language of the Mechanical Garden was incorporated using vertical engraved ridges around the perimeter of the component.

Figure 29: All prototypes of the Gear mount component of the Mechanical Garden



5.7.1 Gear Mounting Base 01

Design

The first gear mounting base had a diameter of 25 mm and a height of 15 mm. Three neodymium magnets were integrated into the underside of the component to provide magnetic attachment to the building plate.

Findings

The mounting base functioned as intended and allowed gears to be positioned freely across the building plate. However, when larger gear trains were constructed, the mounting base could shift under the applied forces. In addition, some students found the small form factor difficult to grasp and reposition. The limited diameter also provided insufficient support for larger gears, causing them to wobble during operation.

5.7.2 Gear Mounting Base 02

Design

To improve stability, the diameter was increased to 30 mm while maintaining a height of 15 mm. The larger footprint allowed four neodymium magnets to be integrated into the design instead of three, increasing the magnetic holding force. Research into these forces can be found in Appendix D.

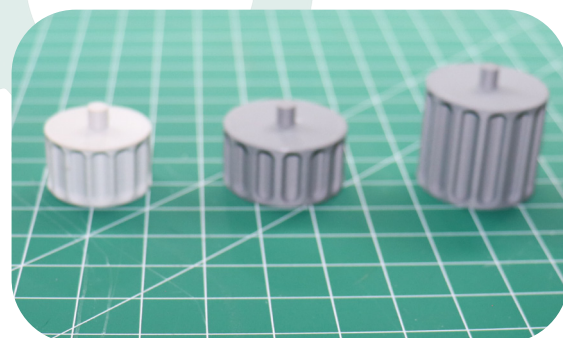
Findings

The increased diameter improved the stability of the mounting base and provided better support for larger gears. The additional magnets reduced unwanted movement when larger gear trains were constructed. Although the larger contact area slightly increased friction, this was

5.7.3 Gear Mounting Base 03

Final Design

The final gear mounting base retained the 30 mm diameter and four-magnet configuration of the previous iteration. However, the height was increased from 15 mm to 21 mm to accommodate changes made to the motor mount and ensure proper engagement between the gears and the drive gear. The increased height also improved the ergonomics of the component by making it easier to grasp and reposition.

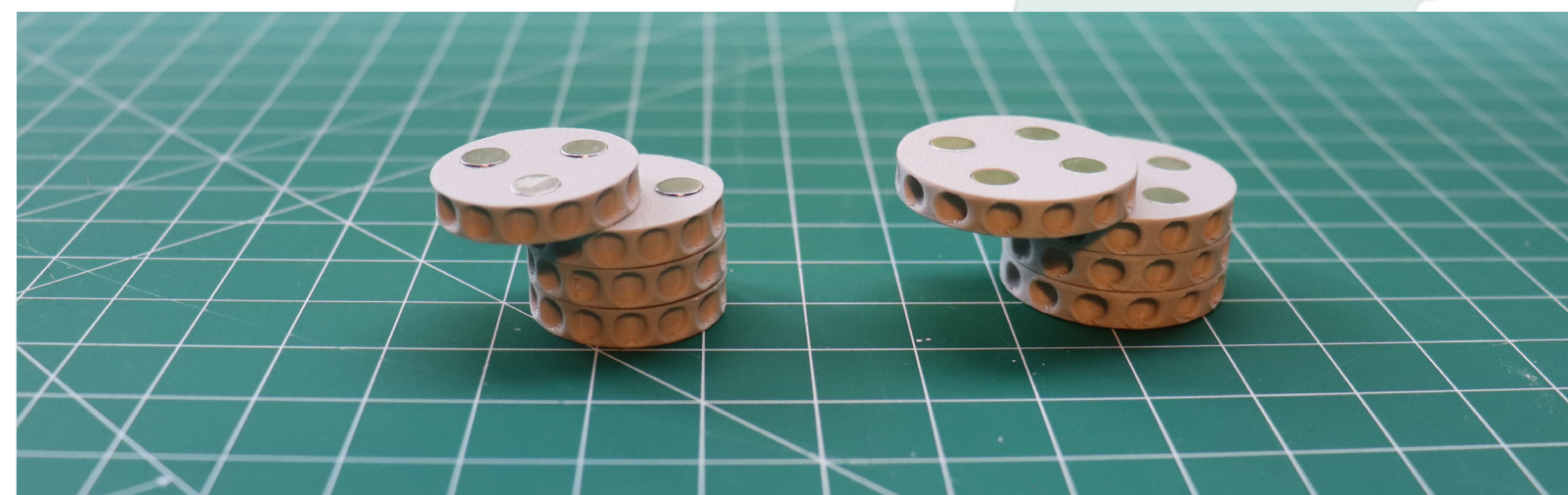
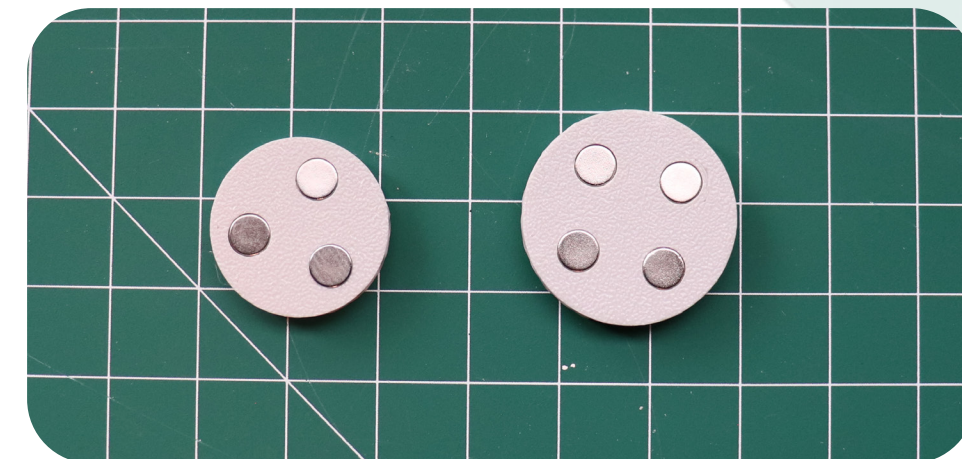
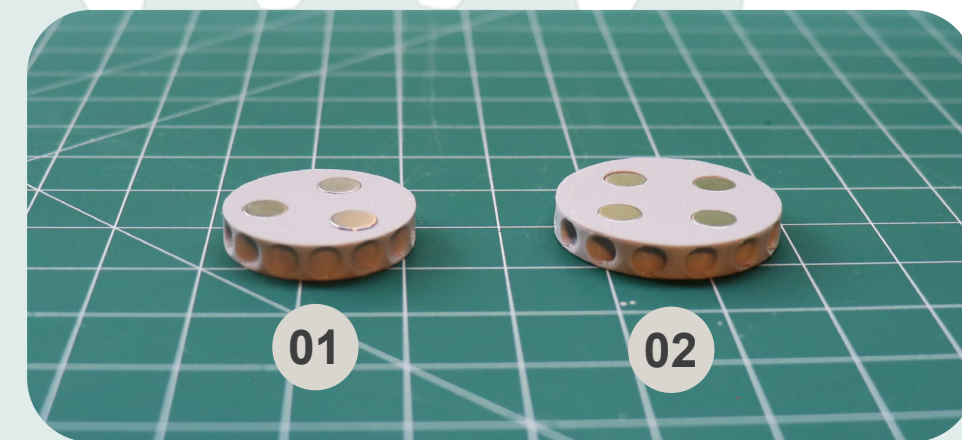


5.8 Magnetic building disc

This component consisted of a 30 mm diameter disc with a height of 5 mm (Figure 30-31). It was designed to increase the height of gear mounting bases in 5 mm increments, enabling the construction of compound gear trains.

To maintain compatibility with the Mechanical Garden system, eight neodymium magnets were integrated into the disc, with four magnets on each side, allowing it to connect securely to other magnetic components.

Figure 30: All prototypes of the Magnetic building disc component of the Mechanical Garden



5.8.1 Magnetic Building Disc 01

Design

The first magnetic building disc was based on the dimensions of the initial gear mounting base and incorporated three neodymium magnets to enable magnetic attachment within the system.

Findings

The component functioned as intended and successfully enabled vertical stacking of components. However, the small form factor occasionally made the disc difficult to grasp and reposition. In addition, the magnet tolerances proved insufficient, causing magnets to become loose after prolonged use.

5.8.2 Magnetic Building Disc 02

Final Design

The final design increased the diameter of the disc to the diameter of the final gear mount design and incorporated additional magnets to improve stability and compatibility with the rest of the system. The larger form factor improved ergonomics by making the component easier to handle, while revised magnet tolerances prevented magnets from loosening during use.

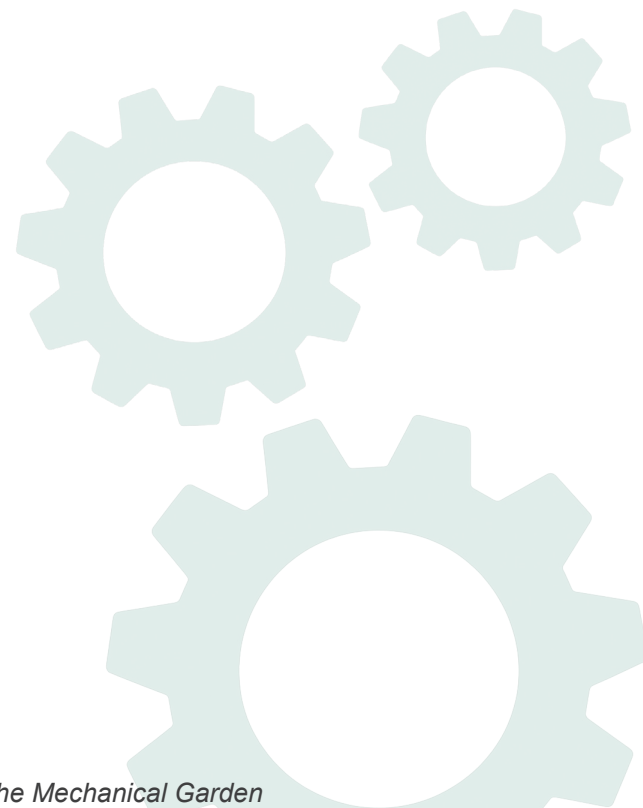
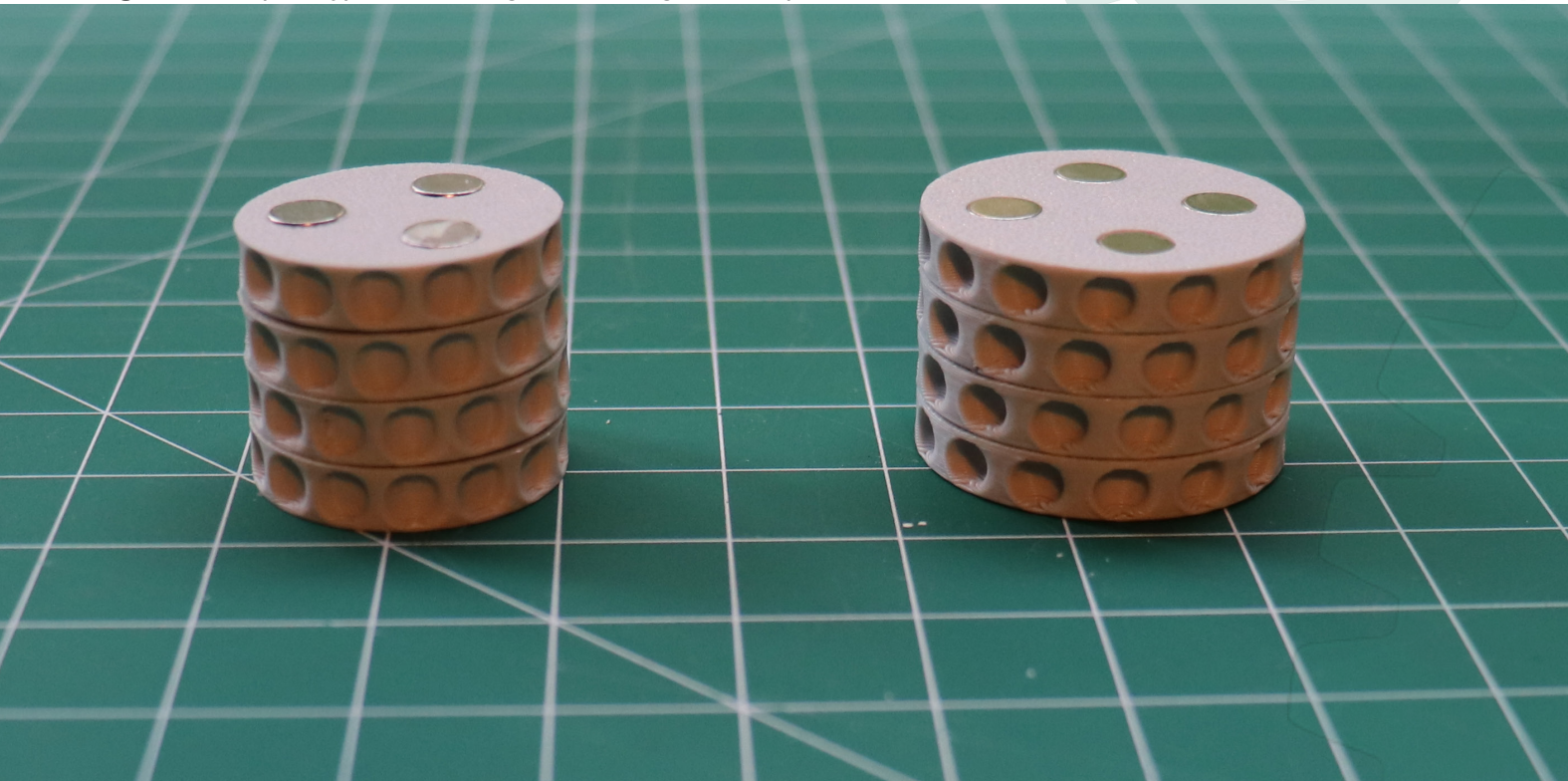


Figure 31: All prototypes of the Magnetic building disk component of the Mechanical Garden



5.9 Magnetic four-bar linkage

The four-bar linkage was identified as an essential component of the Mechanical Garden learning system. It enables students to explore how rotational motion can be converted into oscillating and near-linear movement while also demonstrating a wide range of other motion patterns. Depending on the dimensions and configuration of the linkage, the mechanism can produce rocking motions, reciprocating movements, coupler curves, and complex trajectories commonly used in engineering applications. This versatility makes the four-bar linkage a valuable educational tool for demonstrating the relationship between geometry and motion.

In addition, the design and prototyping of robotic and mechatronic systems form an important part of the DP3 course. Four-bar linkages are frequently applied in robotic products, including grippers, walking mechanisms, articulated arms, and other motion-generating systems. By experimenting with four-bar linkages, students can prototype and evaluate movement concepts that are directly relevant to the design challenges encountered within DP3.

This allows theoretical knowledge of mechanism design to be connected to practical applications in product and robotic system development.

To support experimentation with these mechanisms, it was necessary to develop a system that allowed for rapid prototyping and modification of linkage configurations while maintaining reliable operation when driven by other components within the Mechanical Garden (Figure 32-33).

Figure 32: All prototypes of the Four-bar linkage system component of the Mechanical Garden

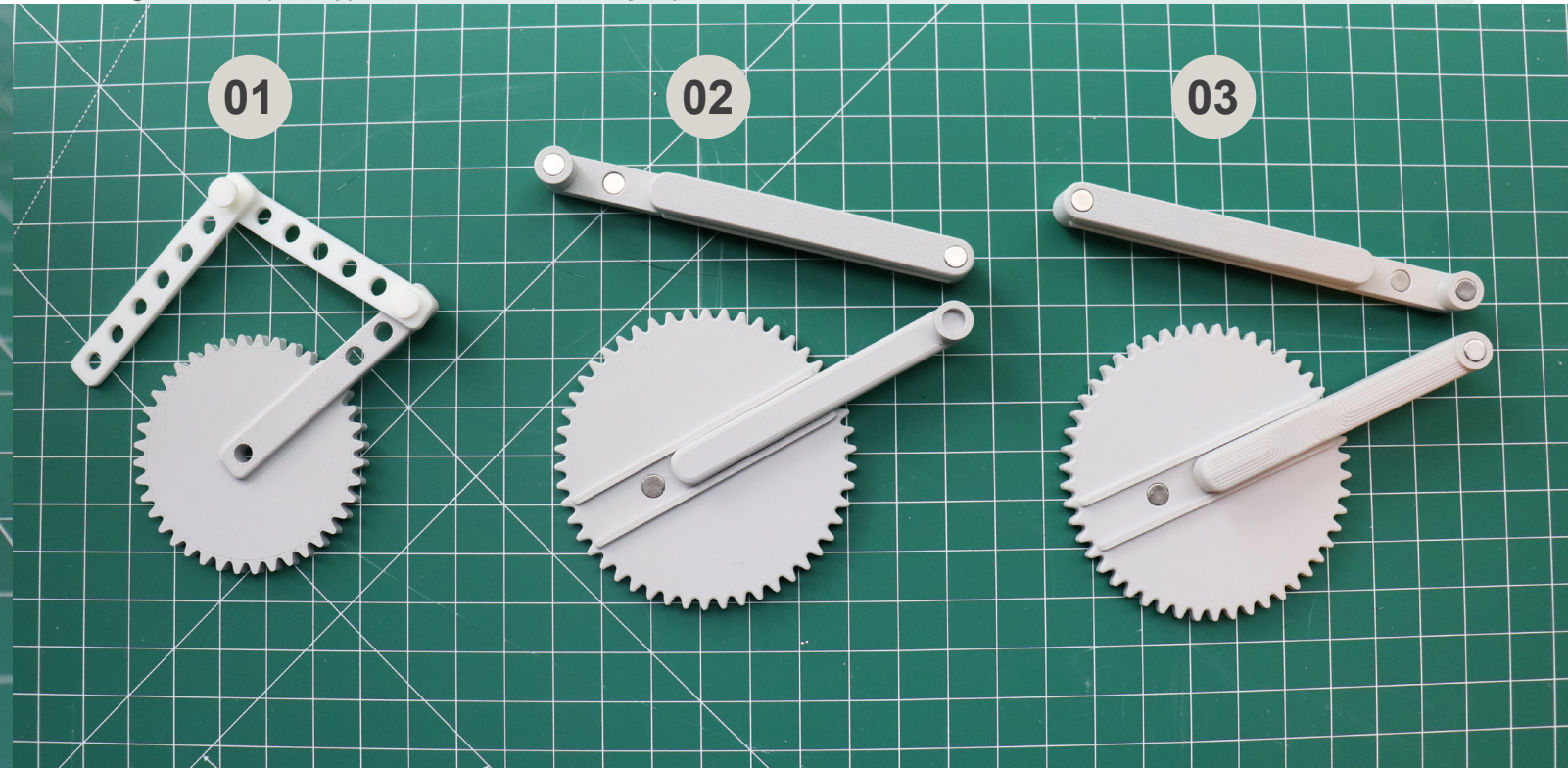
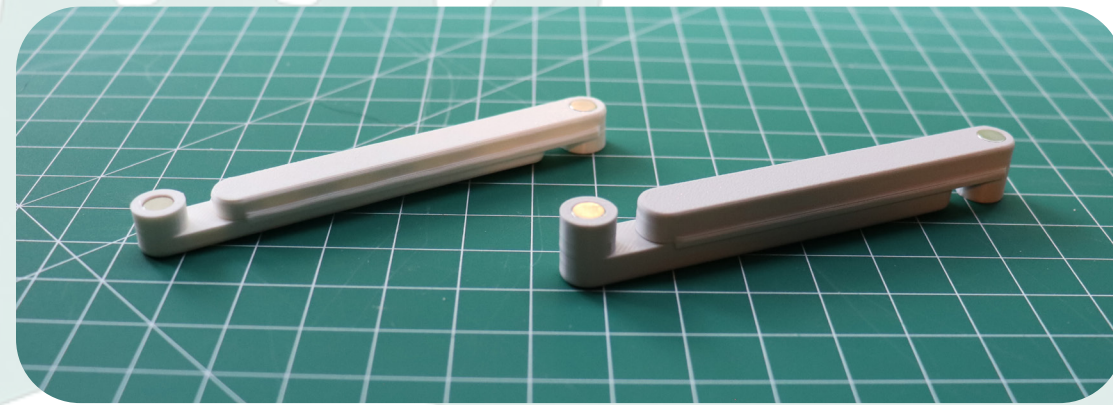


Figure 33: All prototypes of the Four-bar linkage system Bar component of the Mechanical Garden



5.9.1 Magnetic Four-Bar Linkage 01

Design

The first four-bar linkage system consisted of simple bars containing a series of holes. These bars could be connected to specialised gears using press-fit pins, allowing students to construct four-bar linkage mechanisms with different geometries.

Findings

Although the system successfully demonstrated the principles of four-bar linkages, several limitations became apparent during testing. The bars were prone to bending and sagging during operation, reducing the reliability of the mechanism. In addition, constructing and modifying linkages using the hole-and-pin system proved time-consuming. As a result, rapid experimentation with different linkage configurations was difficult, limiting opportunities for exploration and iteration.

5.9.2 Magnetic Four-Bar Linkage 02

Design

To improve flexibility and ease of use, the hole-and-pin system was replaced with a magnetic construction system. Each linkage consisted of two sliding sections that could be adjusted to four predefined lengths and secured using integrated magnets. Magnets were also incorporated into the ends of the bars, allowing them to connect to other linkage components and specialised gears. A complete four-bar linkage could be constructed using three adjustable bars, one of which was attached to a driven gear to provide actuation.

Findings

The magnetic system significantly improved the speed at which linkage configurations could be assembled and modified. Students were able to rapidly adjust linkage lengths and immediately observe the resulting changes in motion. However, testing revealed that the bar attached to the driven gear was positioned too low relative to the other linkage elements. As a result, magnetic attraction caused the linkage to sag towards the driven gear, negatively affecting movement and stability.

5.9.3 Magnetic Four-Bar Linkage 03

Final Design

The final iteration increased the height of the linkage element attached to the driven gear, preventing the mechanism from sagging during operation. In addition, small chamfers were incorporated into the geometry of the bars to improve sliding behaviour during adjustment.

To improve the stability of larger linkage configurations, the driven gear was redesigned to incorporate a magnetic connection on its underside. This gear could be attached to a specialised magnetic gear mount, providing additional holding force during operation.

The modification was introduced because longer linkage configurations generated larger moments on the driven gear. In previous iterations, these forces could lift the gear from its mounting position,

causing it to disengage from the drive gear. The magnetic connection prevented this behaviour and ensured reliable power transmission throughout the mechanism. Testing showed that the revised geometry successfully eliminated the sagging observed in previous iterations while maintaining the flexibility of the magnetic construction system. The magnetic gear connection reliably prevented the driven gear from lifting during operation, even when longer linkage configurations were constructed.

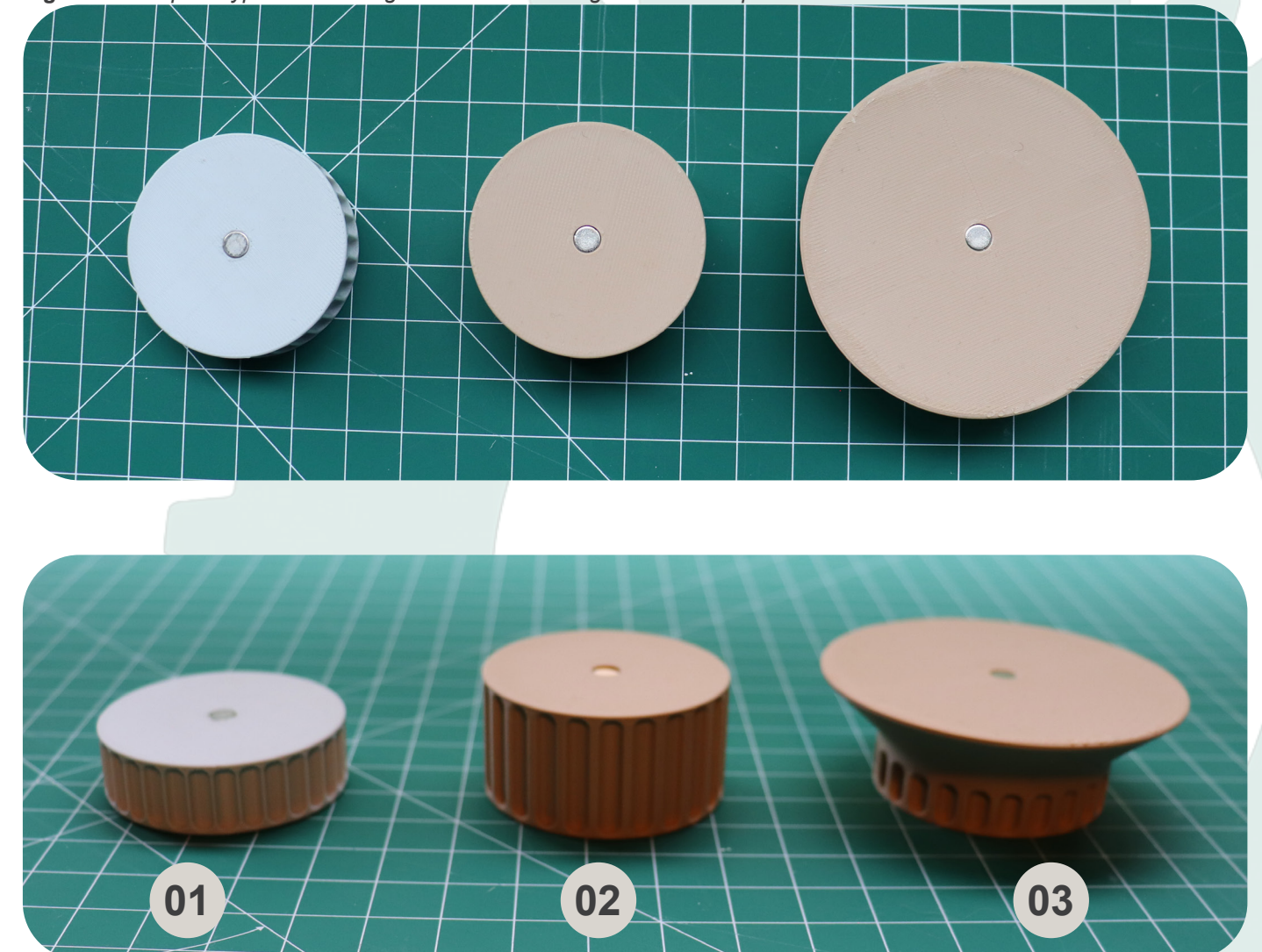
Students responded positively to the ability to rapidly modify linkage dimensions and immediately observe changes in motion. The final design therefore supported both experimentation and reliable operation, aligning with the educational objectives of the Mechanical Garden.

5.10 Magnetic four-bar linkage Holder

To support the four-bar linkage system, a specialised magnetic mounting base was developed (Figure 34). Unlike the gear mounting bases, which use protruding axles, this component provides a flat magnetic connection point for linkage elements. The mounting base has a diameter of 50 mm, providing increased stability when forces are applied through the linkage system. This larger footprint reduces the likelihood of the component falling during operation and improves the reliability of larger linkage configurations.

To maintain compatibility with the rest of the Mechanical Garden, the mounting base can be combined with the magnetic building discs described in the previous section. And they can be stacked on top of each other to create a greater height if needed. This allows the height of the mounting point to be adjusted in 5 mm increments when required. Testing showed that the mounting base provided sufficient stability while still supporting rapid assembly, modification, and experimentation with different four-bar linkage configurations.

Figure 34: All prototypes of the Magnetic four-bar linkage Holder component of the Mechanical Garden

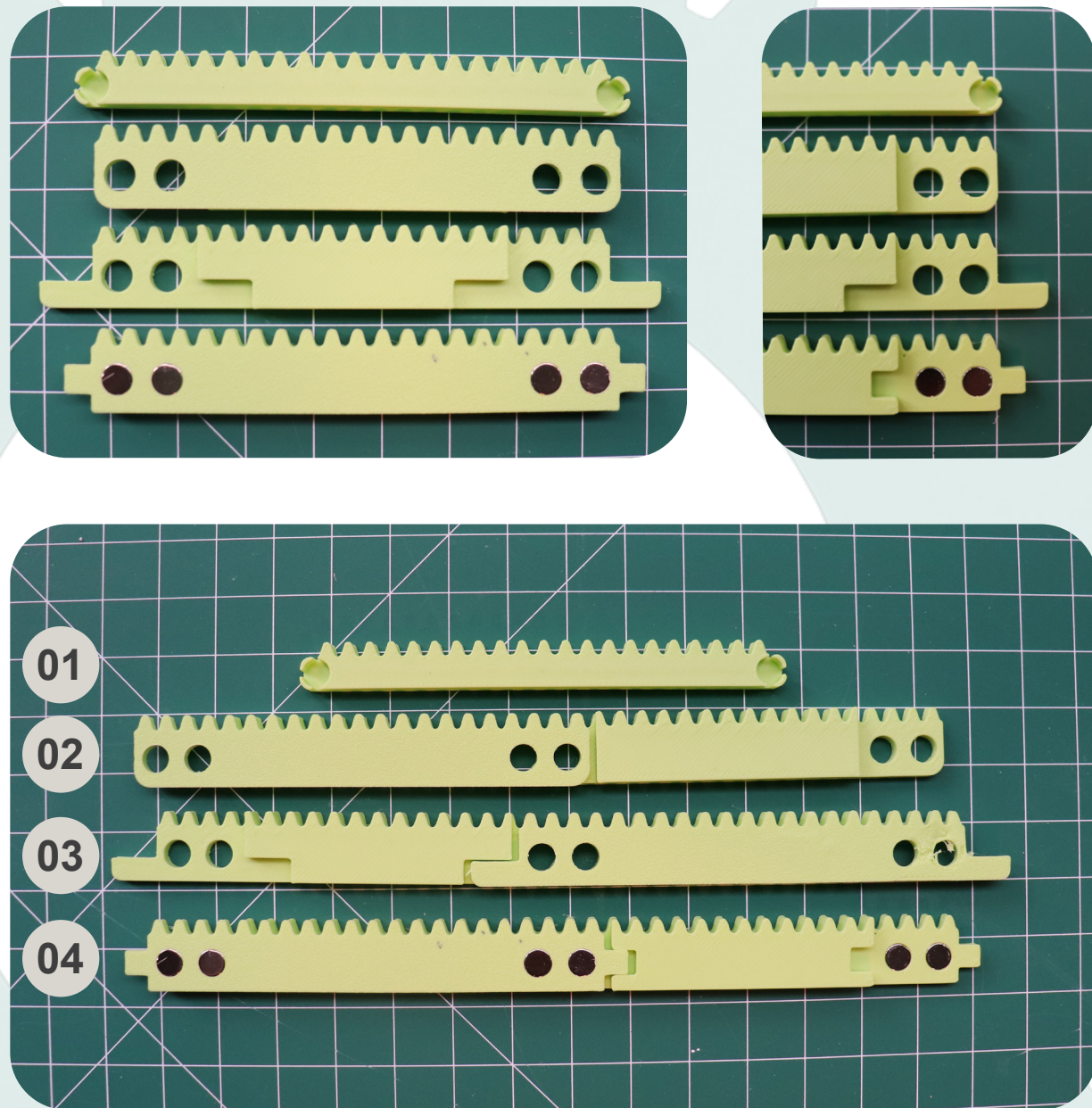


5.11 Magnetic Rack and Pinion

The magnetic rack and pinion system was one of the final additions to the Mechanical Garden. The system was developed after the evaluation phase to demonstrate the expandability of the platform and to provide students with additional opportunities to experiment with different methods of converting rotational motion into linear motion. The rack was designed to be fully compatible with the existing gear system and could also be connected to the four-bar linkage components through integrated magnetic connection points (Figure 35).

To support the construction of larger mechanisms, multiple rack sections could be connected to form longer racks. The following iterations focused on improving the stability and alignment of these connections.

Figure 35: All prototypes of the Magnetic rack and pinion component of the Mechanical Garden



5.11.1 Magnetic Rack and Pinion 01

Design

The first iteration consisted of a straight rack with a single magnetic connection point at each end, allowing multiple rack sections to be connected.

Findings

The rack successfully interacted with the existing gears and enabled the conversion of rotational motion into linear motion. However, when forces were applied to the rack, the connected sections could shift relative to one another. As a result, longer rack assemblies often lost alignment and no longer formed a straight trajectory.

5.11.2 Magnetic Rack and Pinion 02

Design

The first iteration consisted of a straight rack with a single magnetic connection point at each end, allowing multiple rack sections to be connected.

Findings

The rack successfully interacted with the existing gears and enabled the conversion of rotational motion into linear motion. However, when forces were applied to the rack, the connected sections could shift relative to one another. As a result, longer rack assemblies often lost alignment and no longer formed a straight line.

5.11.3 Magnetic Rack and Pinion 03

Design

To address the alignment issues observed in the previous iteration, an interlocking geometry was introduced alongside the magnetic connection system. The magnets provided the holding force, while the interlocking features were intended to prevent sections from shifting relative to one another.

Findings

The interlocking geometry improved alignment and reduced unwanted movement between connected rack sections. However, testing showed that shifting was still possible in certain directions, particularly when larger forces were applied during operation.

5.11.4 Magnetic Rack and Pinion 04

Final Design

The final iteration introduced a revised interlocking geometry that prevented movement in all directions while retaining the magnetic connection system.

remained compatible with the four-bar linkage system, allowing students to combine both mechanisms within a single prototype.

Two magnets were integrated into each connection, providing sufficient holding force while the interlocking features ensured accurate alignment. The design

Testing showed that the revised connection system successfully maintained alignment between rack sections during operation. The rack and pinion system reliably converted rotational motion into

linear motion and expanded the range of mechanisms that could be explored within the Mechanical Garden.

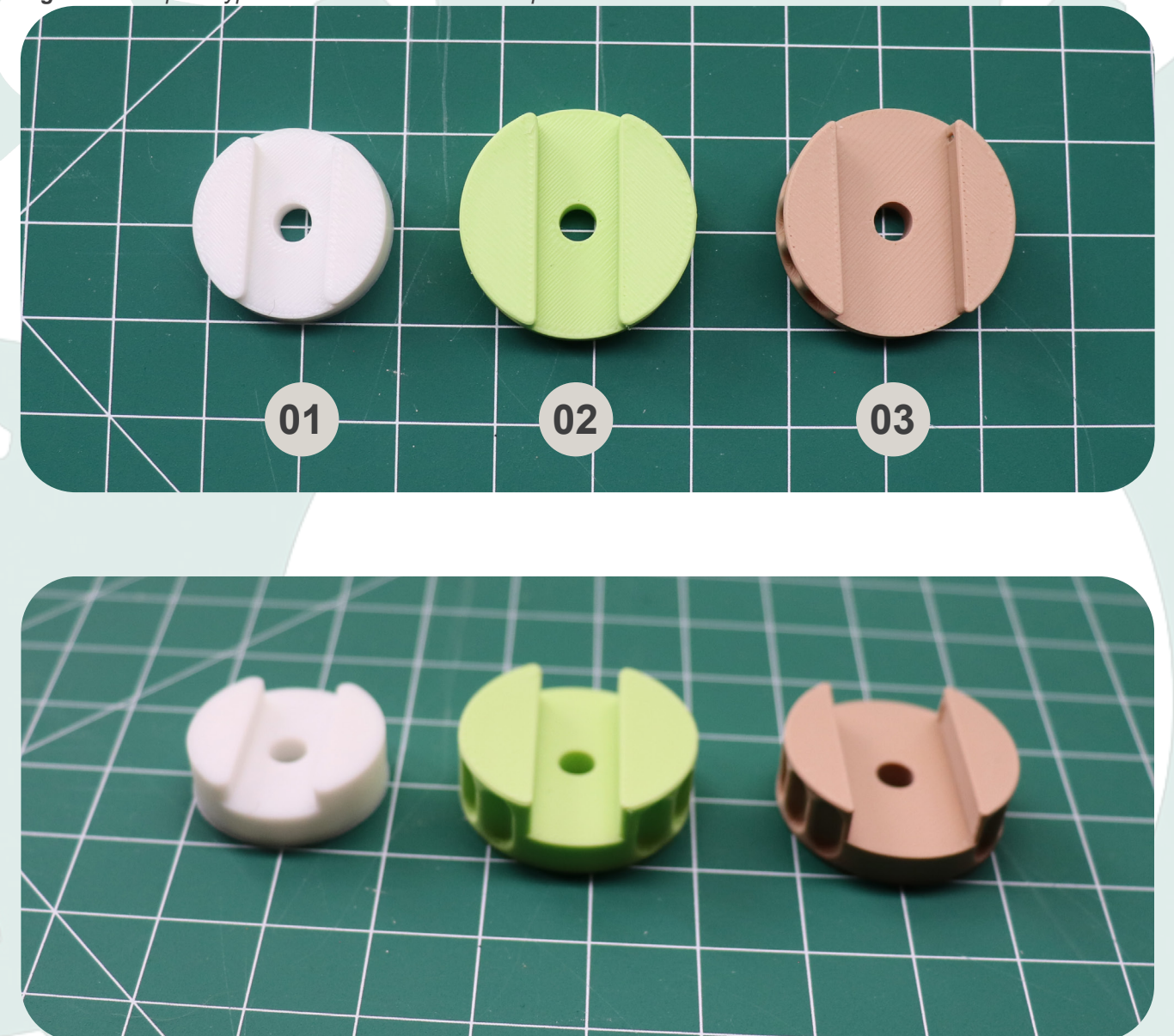
In addition, the ability to connect the rack to four-bar linkage components further increased the opportunities for experimentation and mechanism design.

5.12 Rack channel

To enable controlled linear motion of the rack system, a dedicated rack channel was developed (Figure 36). The component attaches directly to the existing gear mounting base and guides the rack along a predefined linear path. By constraining movement to a single direction, the rack channel ensures reliable engagement between the rack and the driving gear while preventing unwanted lateral movement.

The channel was designed to remain compatible with the modular nature of the Mechanical Garden and can be combined with existing gears, mounting bases, and linkage components. Testing showed that the rack channel provided sufficient guidance for smooth linear motion while maintaining the rapid assembly and experimentation that characterise the Mechanical Garden system.

Figure 36: All prototypes of the Rack channel component of the Mechanical Garden



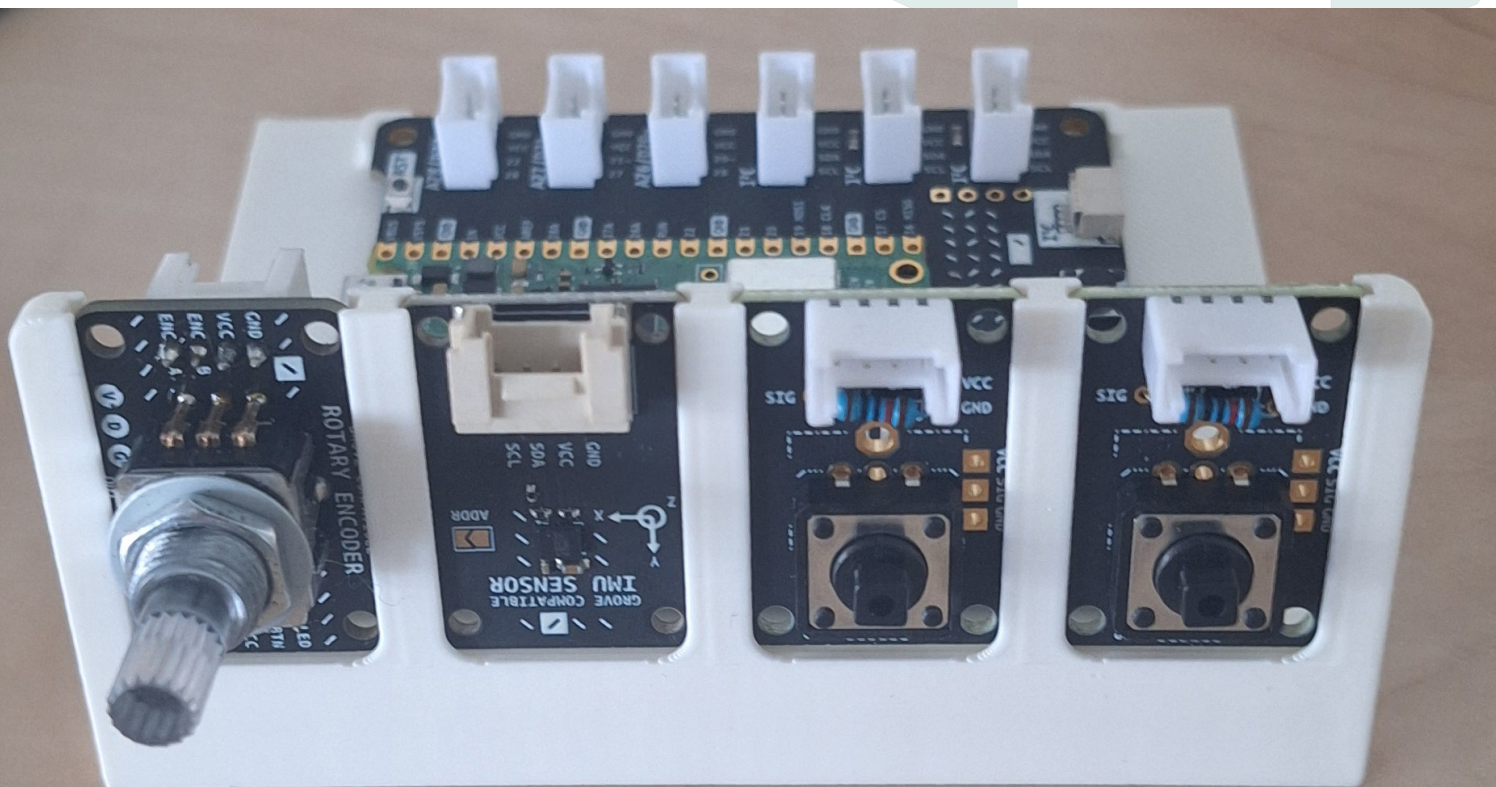
5.12 Electronic Component Holder

During the development of the Mechanical Garden, the CIK was selected as the primary control solution for the stepper motor used as main drive module in the mechanical garden. The CIK provided a reliable and accessible method for controlling motor speed and direction while remaining fully compatible with the existing drive system. The CIK components used in the mechanical garden can be seen in Figure 37.

Furthermore, Bachelor Industrial Design Engineering students are already familiar with the CIK through other courses within the curriculum. This familiarity reduced the learning curve associated

with operating the Mechanical Garden and enabled students to focus on understanding mechanical principles rather than electronic implementation. In addition, students could create their own control programs and configure custom interactions, further supporting experimentation and exploration within the learning environment. Rather than designing and creating a separate controller solution, the students at the IDE faculty are already in possession of the CIK. Using the CIK which the students already possess, saves costs when producing and manufacturing the Mechanical Garden.

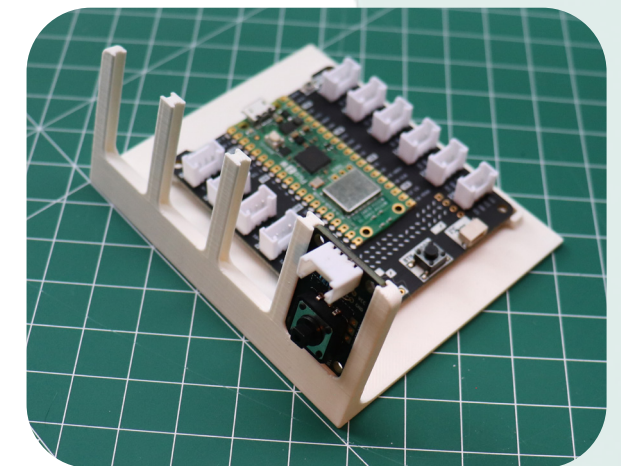
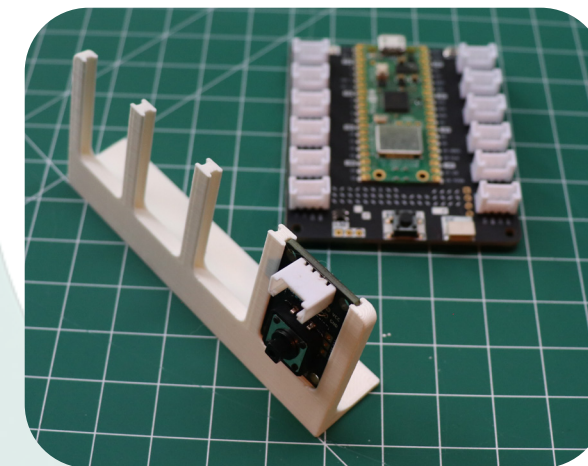
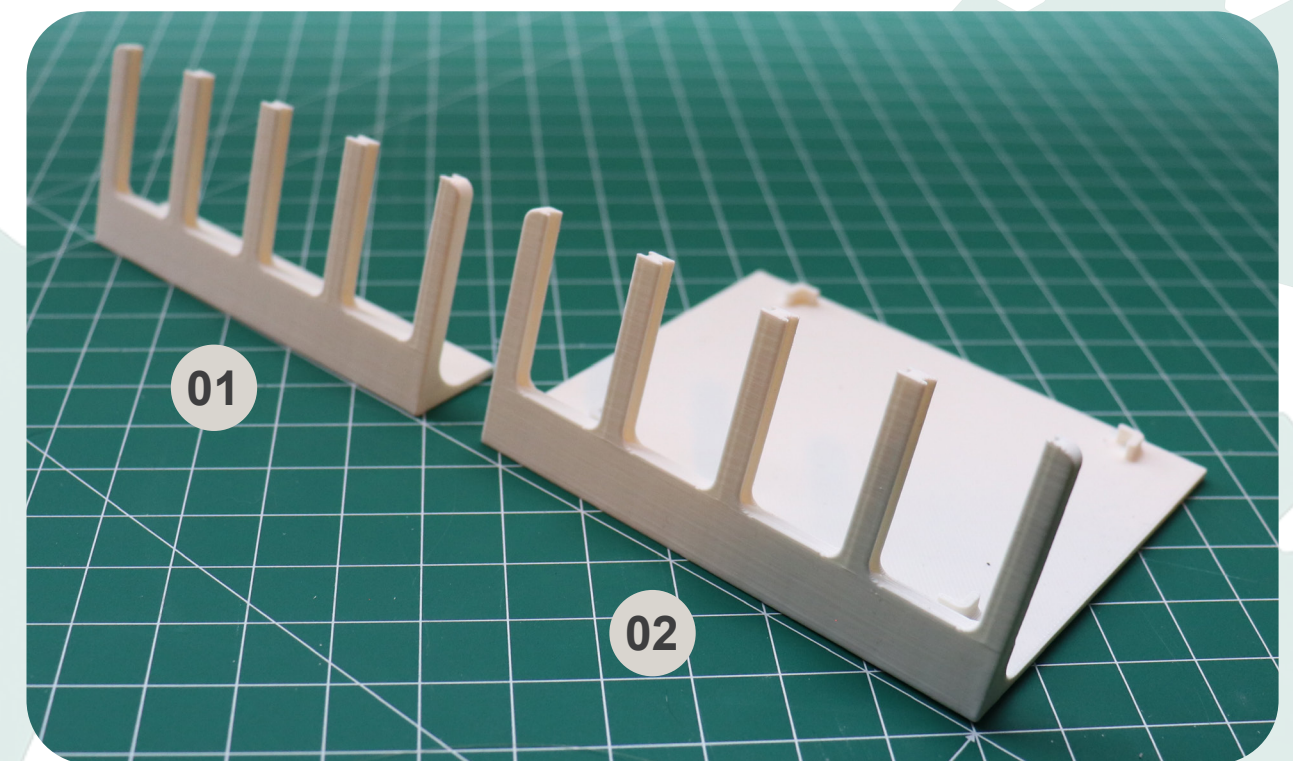
Figure 37: Electronic component holder using components of the CIK



As discussed in Chapter 4.7, the CIK was integrated into the Mechanical Garden to provide students with a familiar and accessible method for controlling and programming the stepper motor.

To support the integration of the CIK, a dedicated holder for buttons, switches, potentiometers, and the microcontroller was required. Without such a holder, components would remain loosely connected to the microcontroller, reducing usability and increasing the risk of damage. In addition, contact between exposed electronic components and the metal building plate could result in short circuits. The following sections discuss the evolution of the electronic component holder and the design decisions that led to the final solution (Figure 38).

Figure 38: All prototypes of the Electronic component holder component of the Mechanical Garden



5.12.1 Electronic Component Holder 01

Design

The first iteration did not include a dedicated electronic component holder. Instead, students were expected to design and construct their own housing using materials such as cardboard. This approach was intended to encourage creativity and provide students with freedom in configuring the electronic controls.

Findings

Discussions with educators indicated that this approach was unsuitable for the intended educational context. The resulting constructions were often visually inconsistent with the Mechanical Garden, and the limited time available within the course made it unrealistic to expect students to design and manufacture their own electronic housings.

5.12.2 Electronic Component Holder 02

Design

The second iteration introduced a dedicated holder designed around the button modules of the StudioLab Interaction Kit. Slots were incorporated into the design, allowing buttons and other input components to be securely inserted and manipulated by the user.

Findings

The holder successfully accommodated the input modules and improved the organisation of the electronics. However, no provision was made for the microcontroller itself. As a result, the electronics remained fragmented and visually cluttered. Furthermore, the exposed microcontroller could still come into contact with conductive surfaces, creating a potential risk of short circuits.

5.12.3 Electronic Component Holder 03

Final Design

The final iteration integrated all electronic components into a single housing, including the microcontroller, buttons, switches, and potentiometers. The design protected the electronics while maintaining

easy access to the controls and allowing components to be reconfigured when required. This resulted in a more robust, organised, and user-friendly solution that aligned with the overall design language of the Mechanical Garden.

5.12.4 Control Interface

Design

The first control interface consisted of four push-buttons that allowed users to directly control the operation of the stepper motor. The buttons provided the following functions:

- 1. Start and stop the motor.
- 2. Rotate clockwise.
- 3. Rotate counterclockwise.
- 4. Oscillating motion.

The interface provided direct access to all available functions and allowed students to quickly operate the Mechanical Garden.

Findings

Although the interface functioned reliably, later stages of the project revealed opportunities to expand the available functionality. Additional control over motor behaviour was considered beneficial for supporting experimentation with mechanisms and observing the effects of different movement patterns. To accommodate these requirements, a second iteration of the interface was developed.

Final Design

The final control interface consisted of three push-buttons and a rotary angle sensor. Rather than assigning a dedicated button to each function, a single button was used to cycle through the available operating modes:

- 1. On
- 2. Continuous rotation
- 3. Oscillating motion
- 4. Off

Two push buttons allowed users to select the direction of rotation when operating in continuous rotation mode. The rotary angle sensor was used to increase or decrease the motor speed in both continuous and oscillating modes. This redesign expanded the available functionality of the stepper motor and therefore allowed students to experiment with more forms of movement, speed and direction.

A custom Python program was developed to control the interface and translate user inputs into motor behaviour. The code can be found in Appendix E. Generative AI tools, including ChatGPT were used during development to support rapid prototyping and modification of the code.

The resulting interface enabled students to quickly operate the Mechanical Garden while retaining the possibility to create



5.13 Developed Educational Support Systems

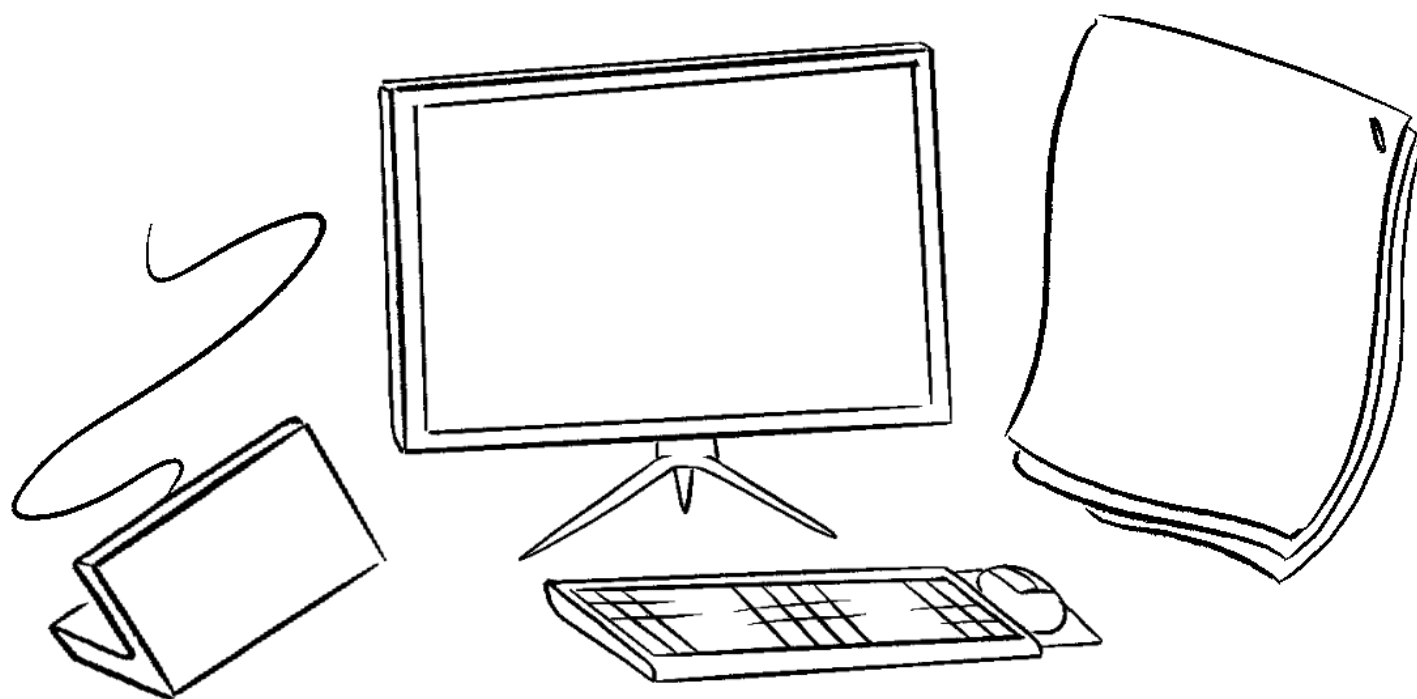
In addition to the physical components of the Mechanical Garden, several supporting tools were developed to enhance its educational value and usability. Evaluations of the previous prototypes demonstrated that freedom of experimentation alone was insufficient to support effective learning. Students required educational guidance to help them engage with the system, opportunities to create their own components without extensive technical knowledge, and an accessible method for controlling the movement of the mechanisms.

Interviews with educators further emphasized the importance of reducing unnecessary complexity. Within the limited time available in educational settings, it is unrealistic to expect students to design every supporting component or interface themselves. The Mechanical Garden should therefore enable students to focus on learning mechanical principles, experimenting with mechanisms, and developing their own solutions rather than overcoming technical barriers.

To address these requirements, three educational support systems were developed: an exercise booklet, a parametric gear designer, and a control interface based on the CIK (Figure 39).

The following sections discuss the development of these systems and their contribution to the overall learning experience.

Figure 39: Visual of physical aspect of all educational support systems



Exercise Booklet

Design

The first version of the exercise booklet consisted of a collection of exercises covering key mechanical concepts relevant to DP3, including gear rotation direction, gear ratios, compound gears, and four-bar linkages (Figure 40). Together, these exercises were intended to provide students with the knowledge required to complete a final assignment in which they designed and constructed a two-dimensional robotic gripper.

Test

To test the effectiveness of the exercises, the booklet was presented to participants during the evaluation of the Mechanical Garden. Participants were asked to follow the exercises while interacting with the learning tool. During this interaction, participants were filmed to observe how they used both the exercise booklet and the Mechanical Garden. Throughout the test, participants were continuously encouraged to provide verbal feedback regarding the exercises and their experience using the learning tool.

Following the evaluation, participants were asked to provide additional feedback specifically on the exercise booklet. The findings from these evaluations were subsequently presented to two educators. Based on the collected feedback and educator input, new iterations of the exercise booklet were developed and evaluated using the same testing procedure.

Findings

Testing revealed that the booklet contained too many instructional exercises. As a result, students spent a considerable amount of time reading and completing

exercises on paper rather than actively experimenting with the Mechanical Garden itself. Discussions with educators suggested that the balance between instruction and hands-on experimentation should be shifted towards practical exploration.

To address this issue, the exercise booklet was redesigned with the productive failure method in mind, this method promotes experiential learning and lets students Generate suboptimal or incorrect solutions that can be used to identify misconceptions and support students in developing a more accurate understanding of the underlying principles (Persaud & Flipsen, 2023). The final excersize booklet can be found in Appendix F.

Rather than beginning with isolated theoretical concepts, students were first presented with a challenging design task. Subsequent exercises then introduced the knowledge and techniques required to successfully complete the challenge. In addition, the focus of the exercises shifted from teaching mechanical concepts directly to demonstrating what could be achieved with those concepts. For example, the topic of gear ratios was reframed as increasing or decreasing speed and torque.

The revised booklet also incorporated example-based exercises in which students first recreated a mechanism and subsequently modified key variables to observe the resulting effects. This approach encouraged students to spend more time experimenting on the Mechanical Garden itself while still providing sufficient educational guidance.

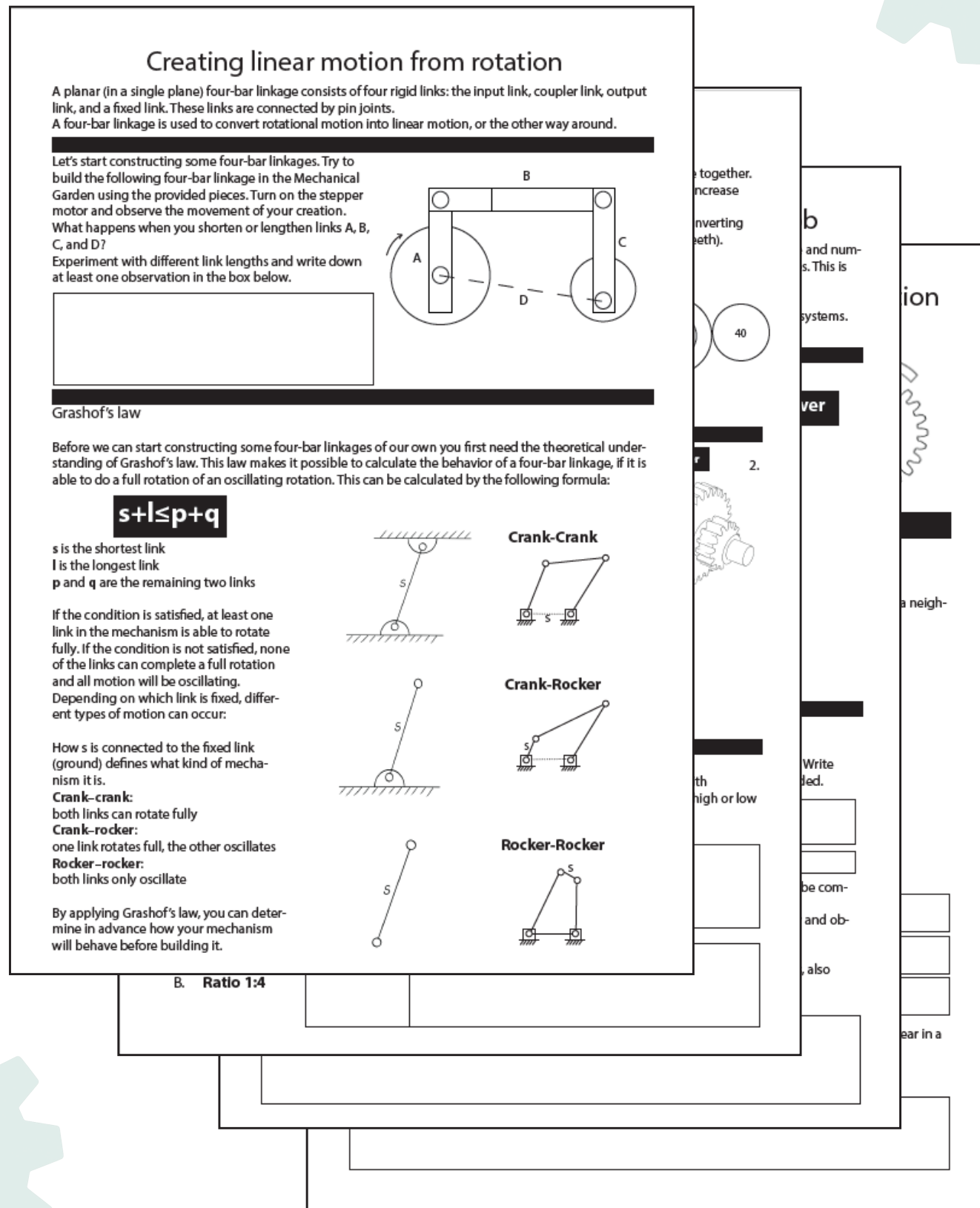


Figure 40: Photograph of the exercise booklet given to students during testing

Parametric Gear Designer

The parametric gear designer was developed to lower the barrier for students to create custom gears for use within the Mechanical Garden (Figure 41). Earlier evaluations showed that designing gears in conventional CAD software required knowledge and skills that many students had not yet developed. Furthermore, the limited time available within the course made it impractical for students to design and model gears from scratch.

As a result, a web-based tool was developed that allows users to generate gears by adjusting a limited number of parameters, after which the resulting model can be exported as an STL file for manufacturing.

The tool was developed using ScriptSolid (ScriptSolid, 2026), an online platform for creating parametric CAD models through scripting. The code can be found in Appendix G. Users can access the design through a web interface, modify predefined variables, and immediately generate customised gears compatible

with the Mechanical Garden. Development of the tool followed an iterative prototyping approach. An initial gear model was created in CAD and used as the basis for the first parametric version.

Successive iterations focused on improving usability and ensuring compatibility with the Mechanical Garden system. Generative AI tools such as ChatGPT (OpenAI, 2026) were used during development to accelerate the creation and modification of the underlying code, enabling rapid iteration and exploration of different design solutions.

The resulting tool allows students to create custom gears by adjusting the number of teeth and the module without requiring extensive CAD knowledge. In doing so, it lowers the technical barriers associated with gear design and enables students to focus on experimentation, customization, and the development of mechanical solutions within the context of DP3.

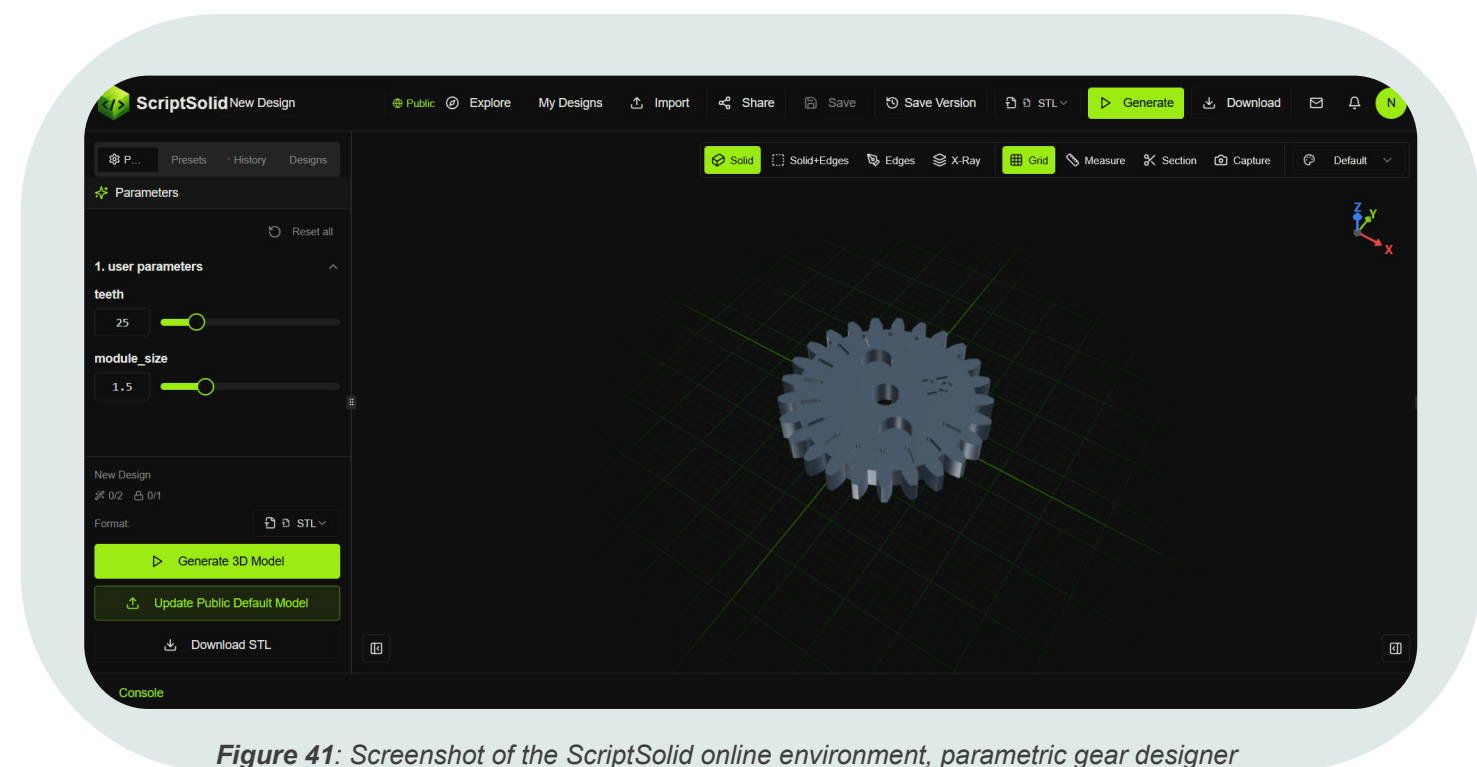
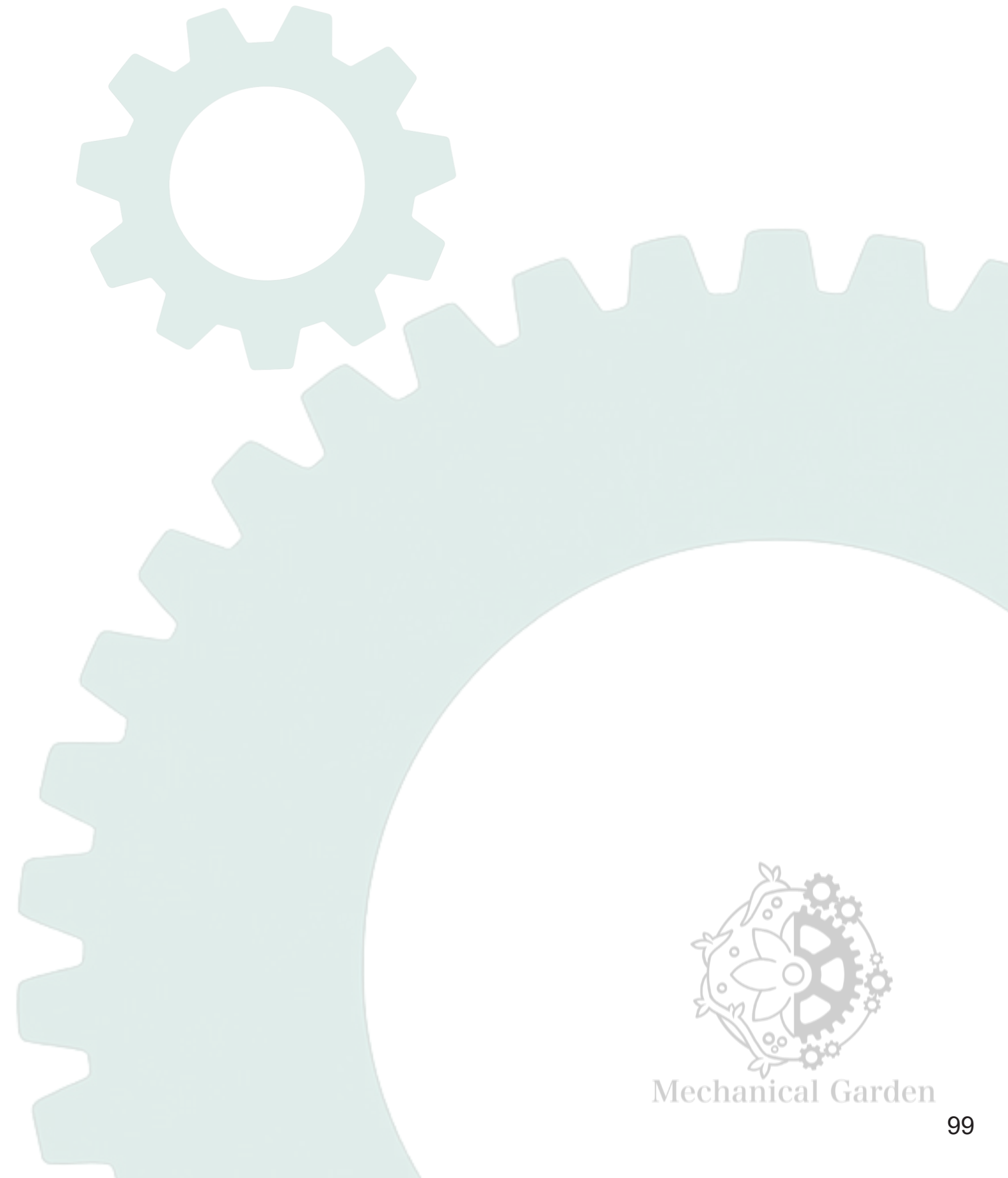


Figure 41: Screenshot of the ScriptSolid online environment, parametric gear designer

Chapter 6.

Mechanical Garden evaluation

This chapter presents the results of the evaluation of the Mechanical Garden. It discusses the findings obtained through the pre-test and post-test, observations, questionnaires, and participant interviews. Together, these results provide insight into both the educational effectiveness of the Mechanical Garden and its performance as an interactive learning tool.



Mechanical Garden

6.1 Evaluation strategy

The evaluation was conducted using a previous version of the Mechanical Garden. Following the evaluation, several improvements were implemented, resulting in the final version presented in Chapter 7. The effectiveness of the Mechanical Garden was evaluated using both educational and technical criteria.

Pre and Post test

To evaluate changes in participants' understanding of mechanical principles, participants were asked to complete a similar test both before and after using the Mechanical Garden: a pre-test and post-test. Both tests consisted primarily of multiple-choice questions, supplemented by a small number of open-ended questions. The tests assessed participants' understanding of gear rotational direction, gear ratios, compound gear systems, and four-bar linkages.

The pre-test and post-test followed the same structure and assessed the same topics. However, the individual questions were modified between the two tests to reduce the influence of memorisation. As a result, participants were required to apply the same underlying principles in both tests, while the specific numbers, configurations, and scenarios differed.

The results of the pre-test and post-test were compared to determine whether participation in the learning activity improved students' understanding of mechanical concepts (Figure 42).

From a technical perspective, the evaluation investigated whether the Mechanical Garden functioned as intended. Attention was paid to whether

students could successfully complete the exercises, construct their own mechanisms, and reliably observe mechanical movement. Additional observations focused on the stability of the magnetic components, durability of the 3D-printed parts, and overall safety of the system during use.

A mixed-methods evaluation approach was adopted. Quantitative data was collected through the pre-test and post-test to assess changes in participants' understanding of mechanical concepts. Additionally participants were asked to fill in a questionnaire about the perceived value of the Mechanical Garden.

Qualitative data was collected through observations and semi-structured interviews to gain insight into participant's experiences, interactions, and perceptions of the Mechanical garden's educational value.

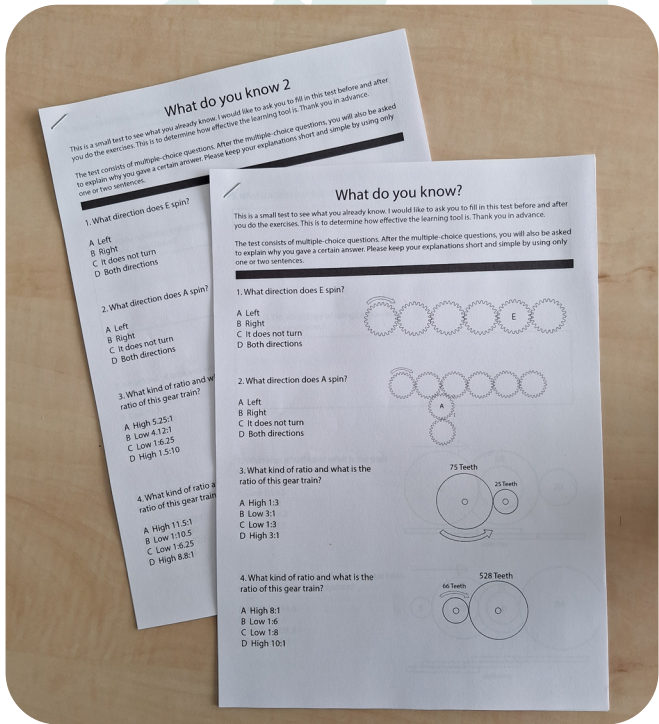


Figure 42: Photograph of Pre and Post test

6.2 Test setup

The evaluation sessions were conducted around a table in either a public or reserved testing space (Figure 43). The test took approximately, 1 hour. All participants provided informed consent prior to participation. The interaction between the participants and the Mechanical Garden was recorded using video to support later analysis.

A maximum of three and minimum of one participant(s) were involved in each session. In Table 3 shows the amount of participants per test.

Test	Amount of participants
01	3
02	1
03	1
04	1
05	1

Table 3: Amount of participants per test session

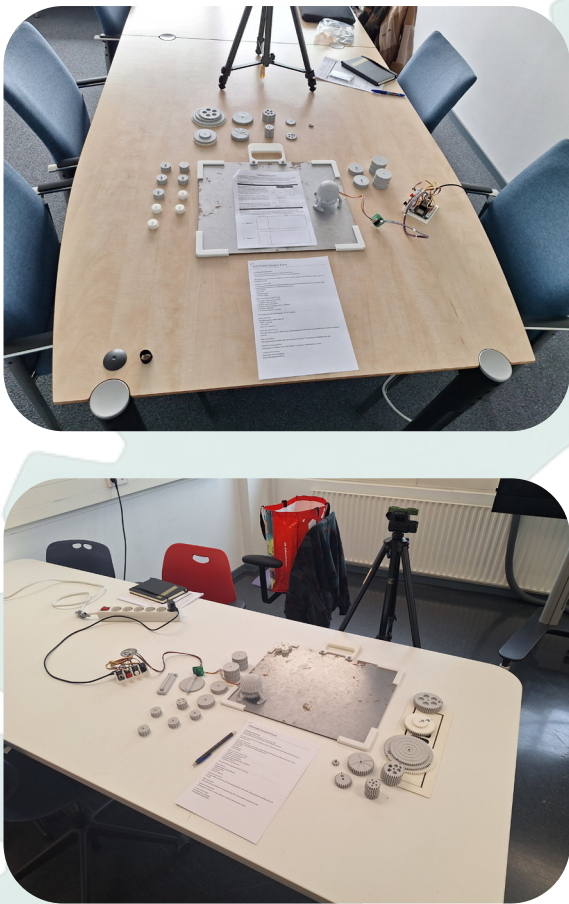
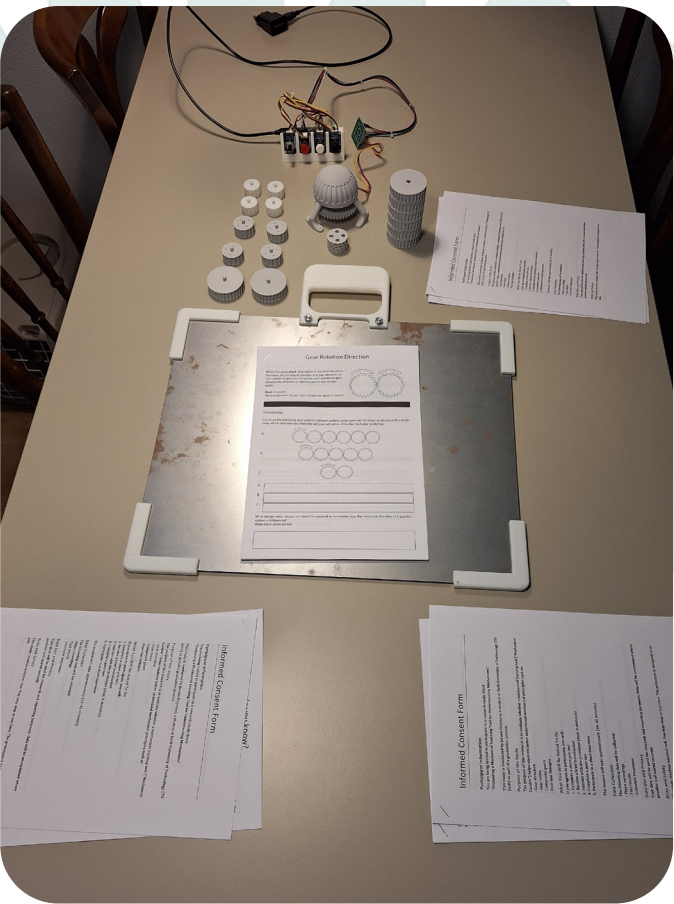


Figure 43: Photograph of all executed test setups

At the start of the session, participants completed the written pre-test to assess their prior knowledge of mechanical movement. A calculator was permitted during the test.

Following the pre-test, participants received a short introduction to the Mechanical Garden, including an explanation of the controls and available components.

Participants then completed the accompanying exercises while interacting with the learning tool. After completing the exercises, participants completed the post-test, participated in a short interview and filled in a questionnaire regarding their experiences, frustrations, ideas and suggestions for improvement.



6.3 Participants

Participants were recruited through invitations distributed within Industrial Design Engineering student communication channels and through educators associated with the DP3 course. The original intention was to evaluate the Mechanical Garden with Bachelor Industrial Design Engineering students, as they represent the primary target group of the learning tool.

Despite multiple recruitment attempts, no Bachelor Industrial Design Engineering students volunteered to participate in the evaluation.

After consultation with supervisors and educators, it was decided to broaden the recruitment strategy and include participants from other educational backgrounds. The purpose of the

evaluation was to investigate both the educational and technical functioning of the Mechanical Garden, and it was therefore considered acceptable to involve participants with varying levels of prior knowledge regarding mechanical systems.

Because all participants completed the same pre-test and post-test, learning gains could be evaluated relative to each participant's initial level of understanding. Consequently, participants with different levels of prior knowledge could still provide meaningful information regarding the educational effectiveness of the Mechanical Garden.

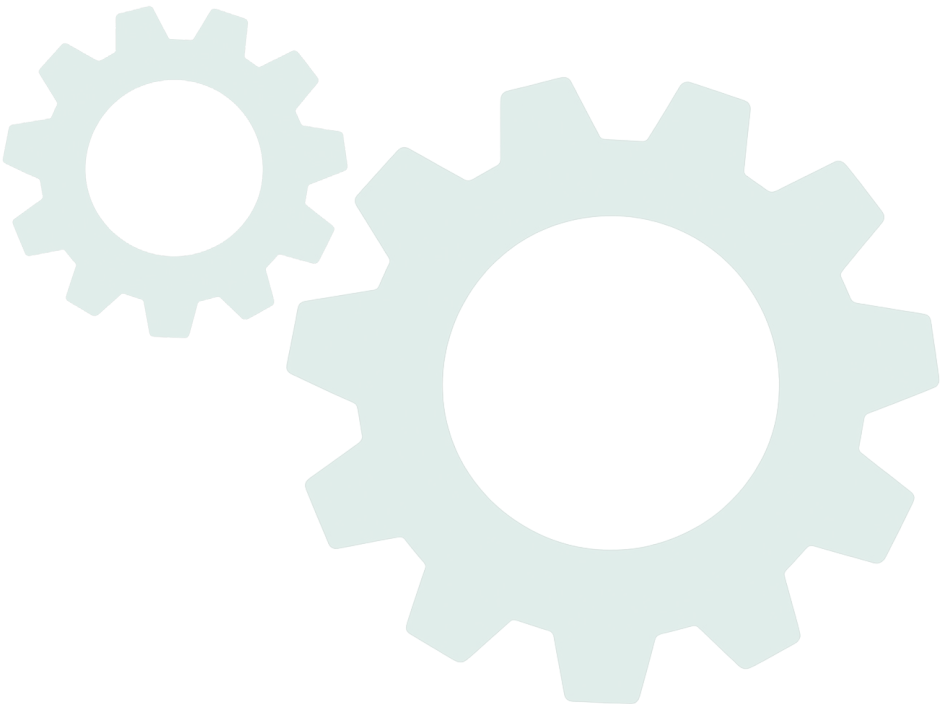
The final participant group consisted of seven participants shown in Table 4.

The diversity of educational backgrounds resulted in varying levels of prior knowledge regarding mechanical systems and mechanism design. This provided insight into how the Mechanical Garden could be used by individuals with different levels of experience.

However, because the participant group did not fully correspond to the intended target group, the results should be interpreted as an initial evaluation of the educational and technical performance of the system rather than a direct validation within the DP3 course context.

Table 4: Numer of participants and their education level

Number of participants	Education
2	Master Industrial Design Engineering students (Design for Interaction)
1	Master Industrial Design Engineering student (Integrated Product Design)
1	Master Computer Science student
1	HBO Communication graduate
1	MSc Biology graduate
1	Bachelor Robotics student



6.4 Pre- and Post-test Results

The individual pre-test and post-test scores of all participants are presented in Figure 44. Across the seven participants, the average pre-test score was **9.1 out of 17** points, corresponding to **54%** correct answers. The average post-test score was **15.5 out of 17** points, corresponding to **91%** correct answers. This represents an **average increase of 6.4 points**, or **37 percentage points**. Improvements were observed for all participants. Although participants came from diverse educational backgrounds, no clear relationship between educational background and test performance could be identified.

Several participants without an engineering background achieved scores comparable to those of engineering students, while some of the lower scores were obtained by participants with engineering-related educational backgrounds.

The results suggest that participants demonstrated a stronger understanding of gear rotation direction, gear ratios, compound gears, and four-bar linkages following interaction with the Mechanical Garden and completion of the accompanying exercises.

While the sample size was limited, the observed increase in scores provides an initial indication that the learning tool supported participants in developing their understanding of the mechanical concepts addressed during the evaluation.

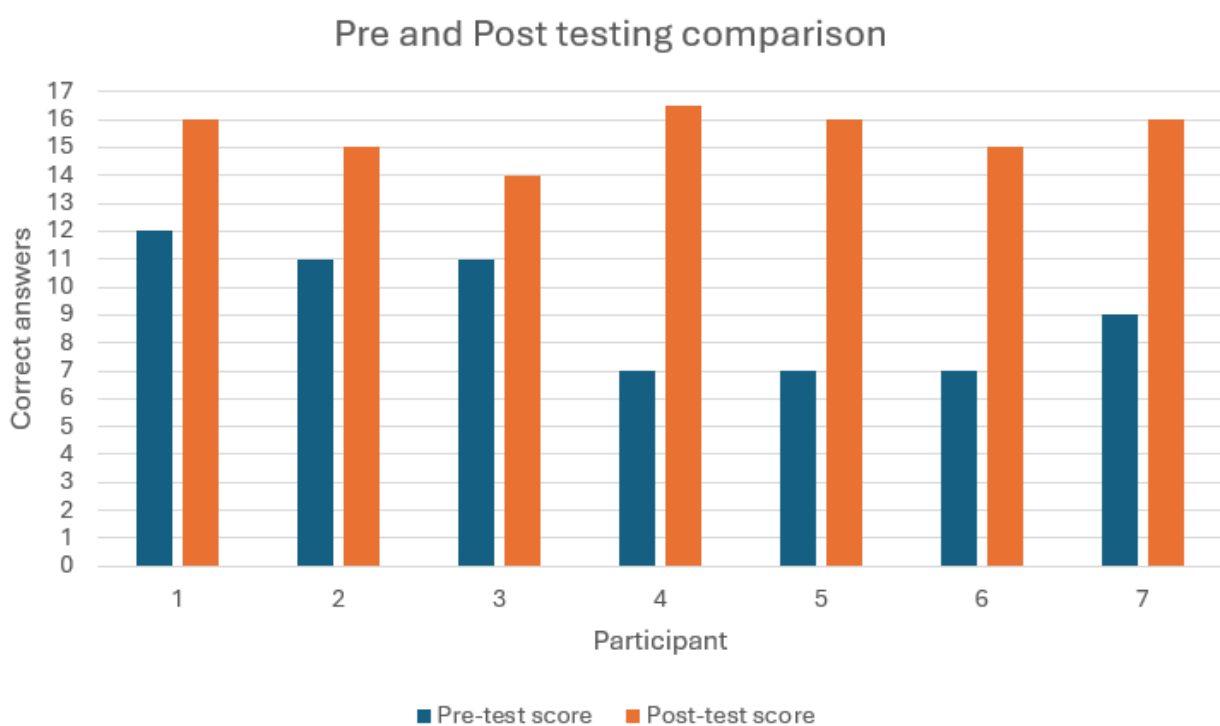


Figure 44: Pre- and Post-test comparison diagram

6.5 Questionnaire Results

Following the evaluation, participants completed a questionnaire consisting of five questions related to the Mechanical Garden and its perceived educational value (Appendix H). Participants were asked to rate each statement on a six-point Likert scale, where 1 represented strong disagreement and 6 represented strong agreement. The questionnaire assessed participants' perceived understanding, confidence, engagement, and perceived educational value of the Mechanical Garden.

The questionnaire assessed whether participants believed that:

1. The Mechanical Garden helped them better understand the mechanical principles covered during the exercises.
2. Interacting with the Mechanical Garden made it easier to understand mechanical movement than learning through theory alone.
3. The Mechanical Garden encouraged them to actively experiment with different mechanical solutions.
4. The Mechanical Garden increased their confidence in applying mechanical principles during a design project.
5. The Mechanical Garden would be a valuable addition to engineering courses and projects, such as the IDE bachelor course DP3.

The average scores for each question are presented in Figure 45. Across all five questions, the average questionnaire score was **5.66 out of 6**.

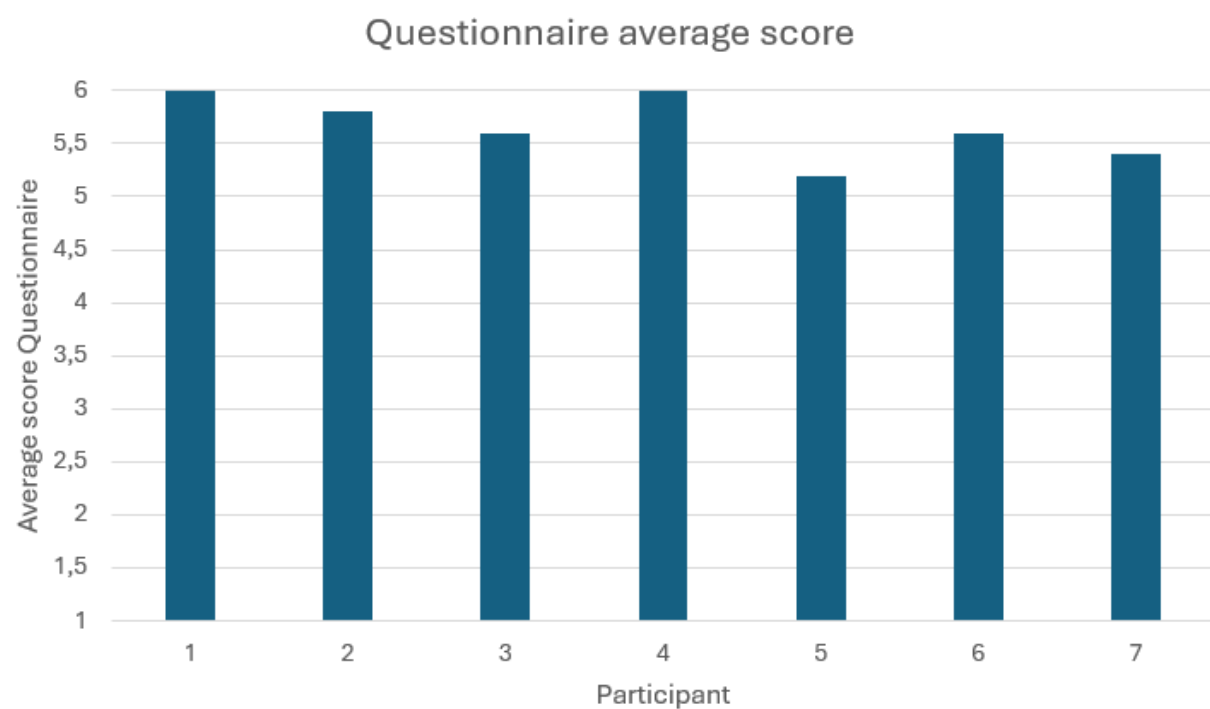


Figure 45: Questionnaire average score per participant diagram

This result indicates a highly positive evaluation of the Mechanical Garden. No participant provided an overall negative evaluation.

Participants reported that the Mechanical Garden helped them better understand mechanical principles, made mechanical movement easier to understand than theory alone, encouraged experimentation, and increased their confidence in applying mechanical mechanisms.

Participants also reported a high perceived educational value of the Mechanical Garden and generally considered it to be a valuable educational tool. The results regarding the potential value of the

Mechanical Garden within the Industrial Design Engineering curriculum should be interpreted with caution. As discussed in Chapter 6.3, not all participants were students within the IDE programme.

Although the educational context and intended application of the Mechanical Garden were explained to all participants, some respondents were unable to evaluate the tool based on direct experience within the curriculum.

Consequently, these findings should be regarded as an initial indication of perceived educational value rather than a definitive evaluation of curricular relevance.

6.6 Technical findings

Several technical and usability-related findings emerged during testing of the Mechanical Garden.

Motor mount

Participants occasionally detached gears from the motor shaft while interacting with the system. In addition, the visibility of the driving gear was limited, making it more difficult to observe the transmission of movement. Repositioning the motor mount on the build plate also proved difficult during use.

Four-bar linkage

Long four-bar linkage configurations occasionally sagged during operation, particularly when participants extended the linkage arms to their maximum length. In addition, magnets integrated within the linkage arms were sometimes attracted to the metal build plate, reducing the stability of the mechanism and influencing its movement.

Gears

Participants frequently attempted to create compound gear systems by combining multiple gears. This behaviour was not explicitly required by the exercises and suggests that participants actively explored more advanced mechanical configurations. However, the existing gear designs provided limited support for creating compound gear systems.

Building plate

Participants frequently collaborated while solving exercises and constructing mechanisms. As a result, the available workspace on the build plate occasionally became limiting during group activities. These observations indicated that

collaborative interaction formed a natural part of the learning process when using the Mechanical Garden.

Exercises

Observations indicated that participants engaged more actively with exercises that encouraged exploration and experimentation than with exercises that primarily focused on following instructions. Productive failure was found to be an effective strategy for promoting interaction with the Mechanical Garden and encouraging students to discover solutions independently.

Overall, participants were able to successfully construct and explore mechanical systems using the Mechanical Garden.

At the same time, the evaluation revealed several opportunities for improving usability, stability, support for experimentation, and collaborative interaction. These findings highlight the primary technical limitations observed during testing.

The resulting design modifications have already been described in Chapter 4 and are reflected in the final Mechanical Garden presented in Chapter 6.



6.7 Interview findings and learning styles

Following completion of the questionnaire, participants took part in a short informal interview. Rather than using a predefined set of questions, participants were invited to freely discuss their experiences with the Mechanical Garden. The primary opening question was: “How was your experience using the Mechanical Garden?”

An unstructured interview format was chosen because the questionnaire had already collected structured feedback regarding educational value, usability, and participant perceptions.

6.7.1 Freedom and guidance

Some students who participated in the test mentioned that they found the exercises they had to do “annoying” they expressed their desire to just build and experiment instead of first reading “boring” lesson materials.

This however was not the case for all students, some valued the exercises a lot because it gave them a clear goal to accomplish.

6.7.2 Suggestions for improvement

Participants expressed considerable interest in the future development of the Mechanical Garden and were curious about the possibility of expanding the system with additional components. Several participants indicated that they enjoyed experimenting with the existing mechanisms and would like to see a wider variety of mechanical elements that would enable the construction of more complex systems.

The informal interviews therefore provided an opportunity for participants to elaborate on their responses, discuss observations that were not covered by the questionnaire, and raise additional suggestions or concerns.

The findings presented in this section are based on recurring themes identified across these discussions.

This showed that designing a learning tool for all students is inherently a difficult challenge. Not every student learns the same way, some prefer other methods or more freedom. For the continuation of the mechanical garden more testing should therefore be done to hone in on developing the best learning experience for all students.

Overall, all interviewed participants enjoyed and valued the experience and

Suggested additions included specialised four-bar linkage components that would enable the construction of functional grippers, worm gears to expand the range of mechanical principles that could be explored, and a vertical metal build plate that would allow students to experiment with mechanisms operating in multiple orientations.

Participants also suggested the inclusion of a compact reference booklet containing relevant formulas, mechanical principles, and theoretical explanations. Such a resource could support students during experimentation by allowing them to quickly consult theoretical information while constructing and testing mechanisms.

6.7.3 Mechanical Garden and different learning styles

The Mechanical Garden accommodates different learning preferences by combining visualisation, physical interaction, guided exercises, and open-ended experimentation. Students are able to observe mechanical principles in action rather than relying solely on theoretical explanations, making concepts such as gear ratios, rotational direction, and four-bar linkages directly visible through physical movement.

The learning tool further supports learning through doing by allowing students to actively build, modify, and test mechanisms. Instead of passively receiving information, students learn through experimentation and interaction with the components.

The open-ended nature of the system also encourages learning through exploration, enabling students to investigate different solutions, test hypotheses, and immediately observe the consequences of their design decisions.

In addition, the accompanying exercises stimulate learning through reflection by

Finally, several participants indicated that the Mechanical Garden could have value beyond the DP3 course and suggested that the system could potentially be applied within other Industrial Design Engineering courses that address prototyping, mechanical design, or product development.

encouraging students to consider why mechanisms behave in a certain way. Incorrect or unexpected outcomes can be analysed and discussed, helping students develop a deeper understanding of the underlying mechanical principles. The modular nature of the Mechanical Garden also supports learning through repetition, as components can be repeatedly assembled, disassembled, and reconfigured to reinforce understanding through continued interaction.

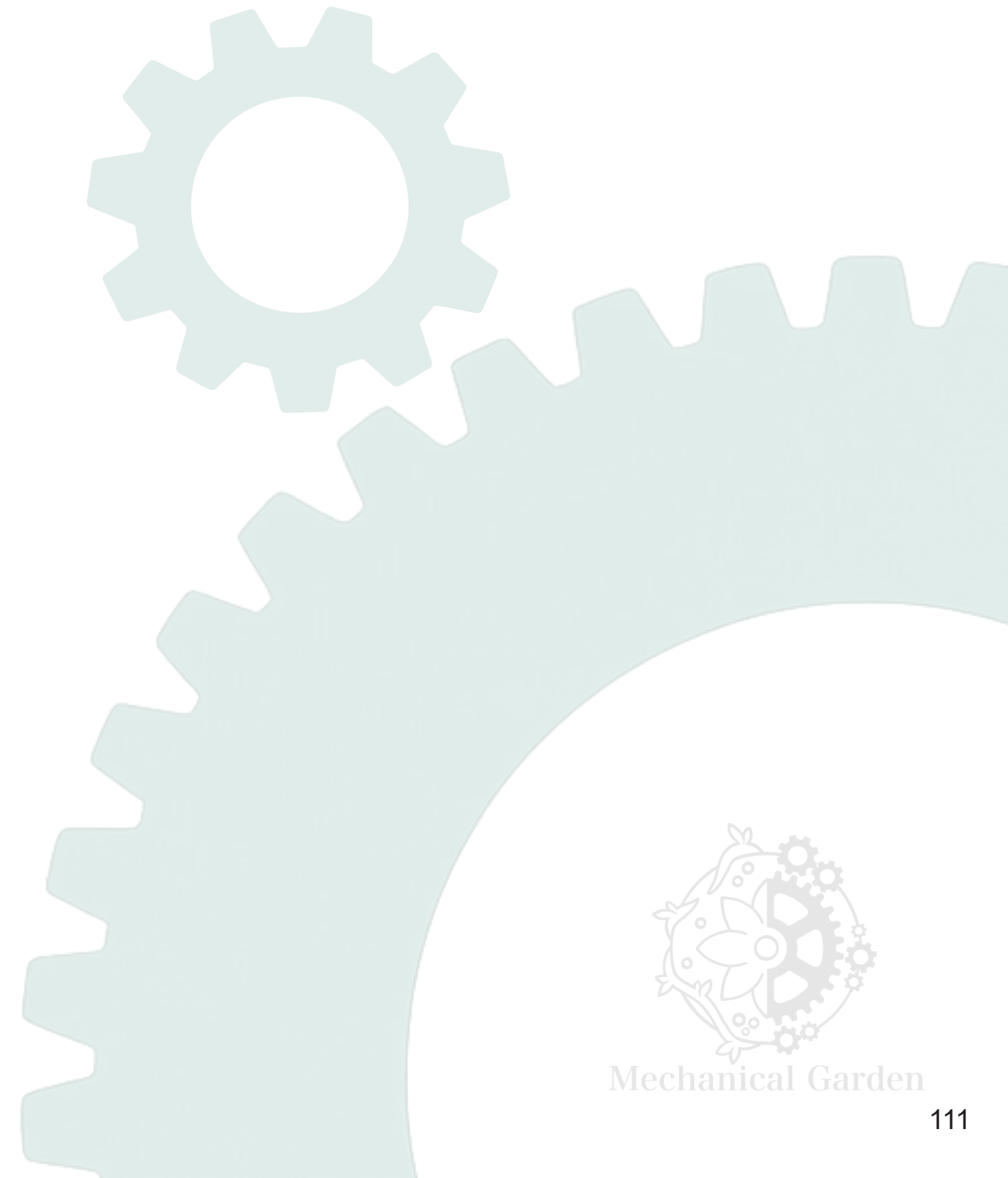
Finally, the Mechanical Garden combines guided and self-directed learning. The exercise booklet provides structure and support for students who prefer a guided approach, while the open construction system enables more experienced students to freely explore, experiment, and develop their own mechanical solutions. As a result, the Mechanical Garden supports multiple complementary approaches to learning and can accommodate a diverse range of students and learning preferences.



Chapter 7.

Discussion

This chapter presents the discussion about the results obtained during the evaluation of the Mechanical Garden conceptual learning tool.



7.1 Educational effectiveness

The evaluation demonstrated that the Mechanical Garden has the potential to support students in developing a better understanding of mechanical principles through active experimentation. Across the seven participants, the average pre-test score increased from 9.1 out of 17 (54%) to 15.5 out of 17 (91%), representing an average improvement of 6.4 points (37%).

Furthermore, all participants improved on their pre-test individual scores following interaction with the Mechanical Garden. In addition, the perceived value questionnaire yielded an overall positive score averaging 5.66 out of 6, indicating that participants perceived the Mechanical Garden as a valuable educational tool that supported their understanding of mechanical principles, encouraged experimentation and could be a useful additional tool for current courses.

Although the participant group was limited (7 participants), these findings suggest that combining physical interaction with guided learning activities can support conceptual understanding of mechanical systems. During the evaluation, participants were able to immediately observe the consequences of modifying gears, linkages, and transmission systems while actively experimenting with different configurations.

Rather than learning exclusively through lectures or static illustrations, students could directly relate theoretical concepts to observable mechanical behaviour.

These findings are consistent with the literature discussed in Chapter 2. Research on active learning, embodied cognition, and tangible interaction suggests that physical interaction supports conceptual understanding by allowing learners to experience abstract concepts through direct manipulation. The observations made during this project support this perspective, as participants frequently experimented with multiple solutions before arriving at the correct mechanical behaviour. This iterative process of constructing, observing, modifying, and evaluating mechanisms appears to contribute to a deeper understanding than passive observation alone.

An interesting finding was that no clear relationship was observed between participants' educational background and their learning gains. Several participants without an engineering background achieved post-test scores comparable to engineering students, while some engineering students achieved relatively lower scores.

Although the participant group was too small to draw definitive conclusions, this suggests that prior engineering education alone may not determine conceptual understanding of mechanical principles and that the Mechanical Garden may be accessible to learners with diverse educational backgrounds.

7.2 Design knowledge Generated through the projects

Beyond evaluating the educational effectiveness of the Mechanical Garden, the iterative design process generated several insights regarding the design of conceptual learning tools.

One important finding was that reducing the effort required to construct and modify mechanisms appears to be important and increase opportunities for experimentation. Earlier prototypes such as the Pocket Construction Prototyper required considerable assembly before meaningful experimentation could begin.

Throughout the design process, simplifying construction and making it more accessible and easier to manipulate and adjust the mechanical components of the prototypes, gradually became a higher priority than increasing the number of available components. By reducing the time required to assemble and adjust mechanisms, students were able to spend more time exploring mechanical behaviour, comparing different solutions, and understanding the relationships between individual components.

A second insight concerns the importance of immediate visual feedback. The Mechanical Garden allows students to directly observe the effects of changing gear ratios, rotation directions, and linkage configurations. This immediate relationship between design decisions and mechanical behaviour appeared to support conceptual understanding by making otherwise abstract principles directly visible. Rather than interpreting theoretical explanations, participants could immediately verify whether their expectations matched the observed

movement and adjust their designs accordingly.

The evaluation also demonstrated the importance of balancing structured learning with opportunities for independent exploration. The first tests with previous iterations of the Mechanical Garden showed that not all students responded well to a fully "open" explorative learning tool. The exercises provided guidance to introduce new concepts and introduced the participants to examples, which they could construct. While still allowing participants to experiment freely with different mechanical solutions. This combination appeared to encourage curiosity without removing the educational focus of the workshop.

Finally, the project suggests that introducing a conceptual learning stage before functional prototyping may help bridge the gap between theoretical instruction and practical implementation of these theories in the designs of students. In many design projects, students are expected to simultaneously solve mechanical, manufacturing, aesthetic, and user-related challenges.

The Mechanical Garden allows students to first explore individual mechanical principles, experiencing and understanding them, before integrating them into complete product concepts.

This intermediate learning stage may enable students to approach later design projects with greater confidence and a broader understanding of possible mechanical solutions.

7.3 Limitations

Several limitations should be considered when interpreting the findings of this study. First, the evaluation involved only seven participants, limiting the extent to which the results can be generalised. Furthermore, the intended target group of Bachelor Industrial Design Engineering students could not be recruited despite multiple recruitment attempts. Consequently, participants from different educational backgrounds were included. While this provided valuable insight into the accessibility of the Mechanical Garden, the evaluation should be considered an initial assessment rather than a direct validation within the DP3 course.

In addition, the evaluation primarily investigated short-term learning effects, before and immediately following interaction with the Mechanical Garden. It therefore remains unclear to what extent the observed improvements are retained over longer periods of time or how the knowledge is transferred to subsequent design projects. Future research should investigate the long-term educational impact of the Mechanical Garden within its intended educational context.

Finally, the current version of the Mechanical Garden focuses on a limited selection of mechanical principles. Although these mechanisms were selected based on observations and educator interviews expanding the available modules could further increase the educational value of the system and broaden its applicability to other engineering and design courses.

7.4 Overall reflection

This project demonstrates that physical conceptual learning tools can complement existing engineering education by providing students with opportunities to actively experiment with mechanical principles before applying them within larger design projects.

It shows that giving students a platform with prebuild building components allows the students to more easily start prototyping and experiencing new ideas. Rather than replacing existing lectures or prototyping activities, the Mechanical Garden introduces an intermediate learning stage that helps bridge the gap between theoretical knowledge and practical application. The Mechanical Garden acts as a learning/prototyping platform which can be consulted before the student continues with further prototyping.

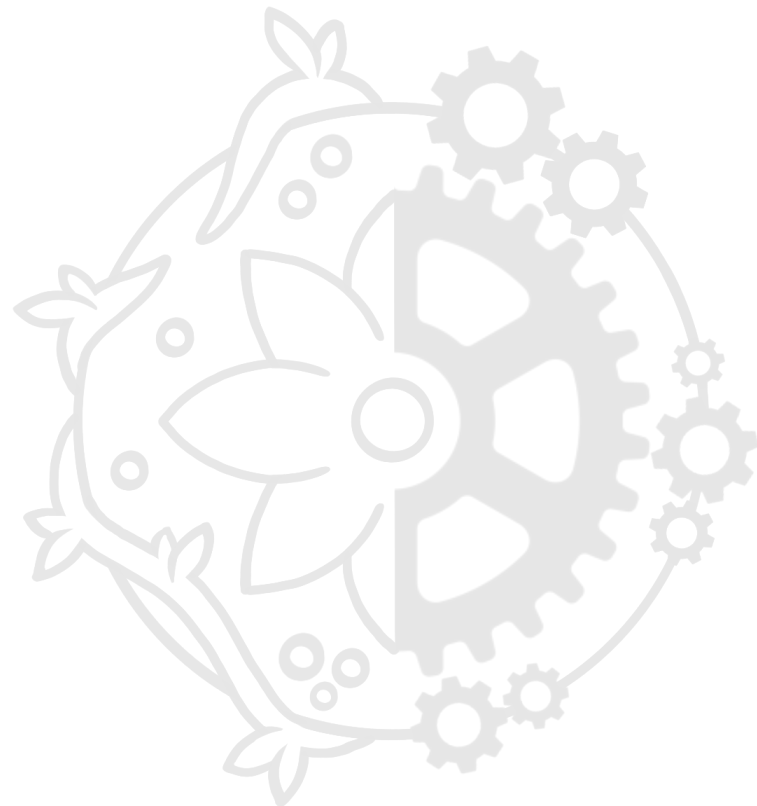
Beyond the development of the Mechanical Garden itself, this research contributes insights into the design of tangible conceptual learning tools. The findings suggest that reducing construction effort, providing immediate visual feedback, encouraging active experimentation, and combining structured exercises with open exploration can support students in developing a more intuitive understanding of mechanical principles.

Although additional research is required to validate these findings within larger educational settings, the Mechanical Garden demonstrates how tangible interaction can contribute to engineering education by supporting conceptual experimentation, exploration and understanding before functional prototyping begins.

Chapter 8.

Final Mechanical Garden design Post-Evaluation.

This chapter presents the final version of the Mechanical Garden conceptual learning tool, incorporating the feedback and improvements resulting from the evaluation. It also describes the supporting systems developed during this project and outlines proposed systems for future implementation and expansion.



Mechanical Garden



8.1 Final Mechanical Garden

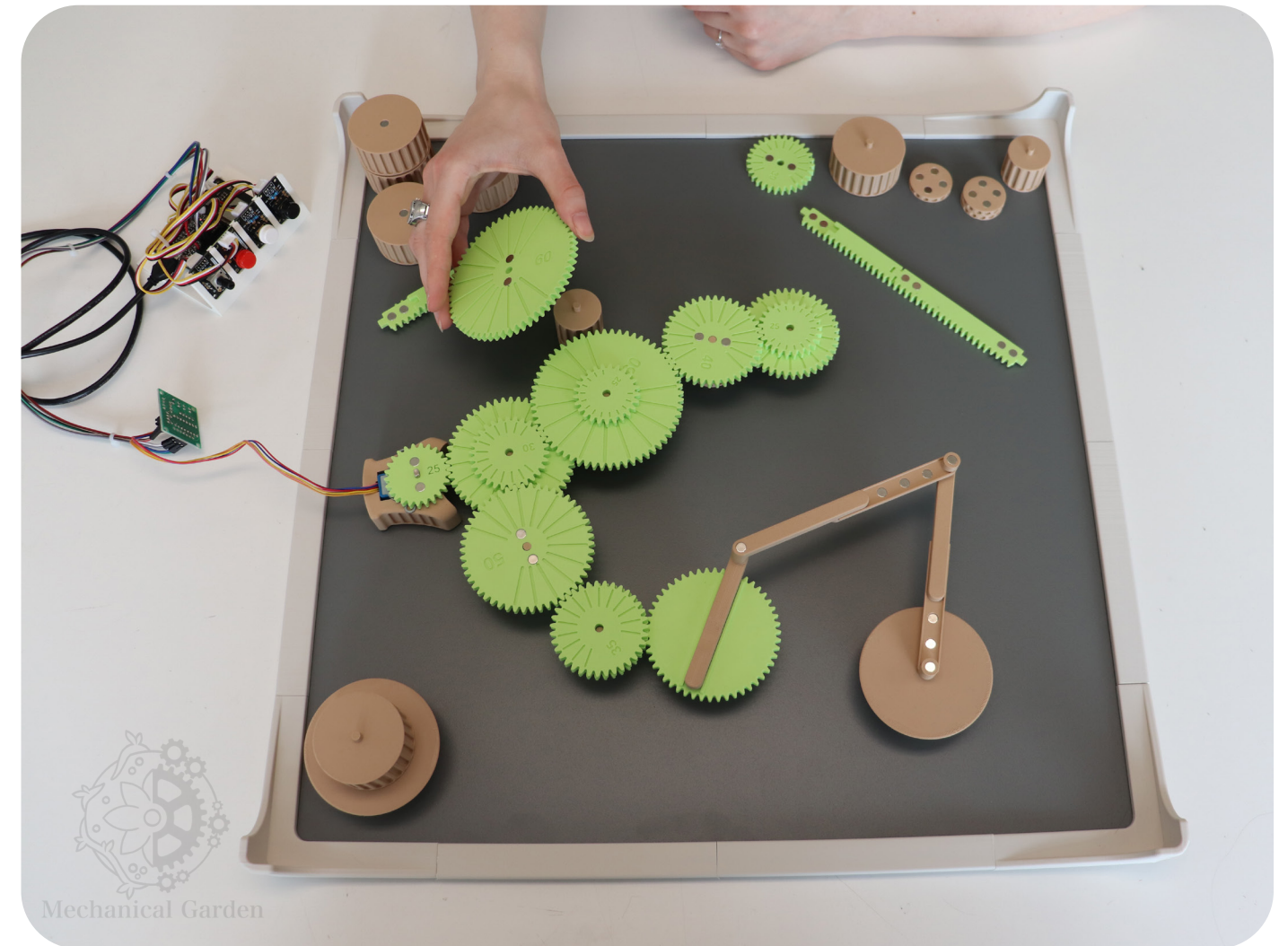
The final Mechanical Garden is a modular educational learning system designed to support students in understanding, experimenting with, and applying mechanical principles. The system combines physical construction components, educational exercises, digital support tools, and an interactive control interface to create an environment in which students can learn through experimentation and prototyping.

Figure 46 shows the final Mechanical Garden. The system consists of a magnetic build plate, a modular gear system, adjustable four-bar linkages, a rack-and-pinion mechanism, electronic control components, and several educational support systems.

Together, these elements enable students to construct, modify, and evaluate mechanical systems while directly observing the resulting movement.

The final design addresses the design requirements identified in Chapter 4 by combining freedom of construction, stability during interaction, support for experimentation, and accessibility for students with different levels of understanding mechanical principles.

Figure 46: Final Mechanical Garden prototype



8.2 Physical Construction System

The physical construction system consists of a magnetic metal build plate onto which Magnetic components can be attached and repositioned. Magnets provide sufficient holding force to maintain stability during operation and offer full freedom on the building plate, also allowing students to rapidly modify and prototype their constructions.

The system includes a collection of modular components (Figure 47):

- 1. Magnetic Four-bar linkage
- 2. Magnetic Rack and Pinion
- 3. Magnetic Parametric Gear
- 4. Moter Gear
- 5. Moter Mount
- 6. Gear Mounting Base
- 7. Big Gear Mounting Base
- 8. Magnetic Gear mounting base
- 9. Big Magnetic Gear mounting base
- 10. Rack Channel
- 11. Magnetic Building Disc

All components were designed to remain compatible with the same magnetic building system and standardized height dimensions. This allows mechanisms to be combined freely while maintaining reliable operation.

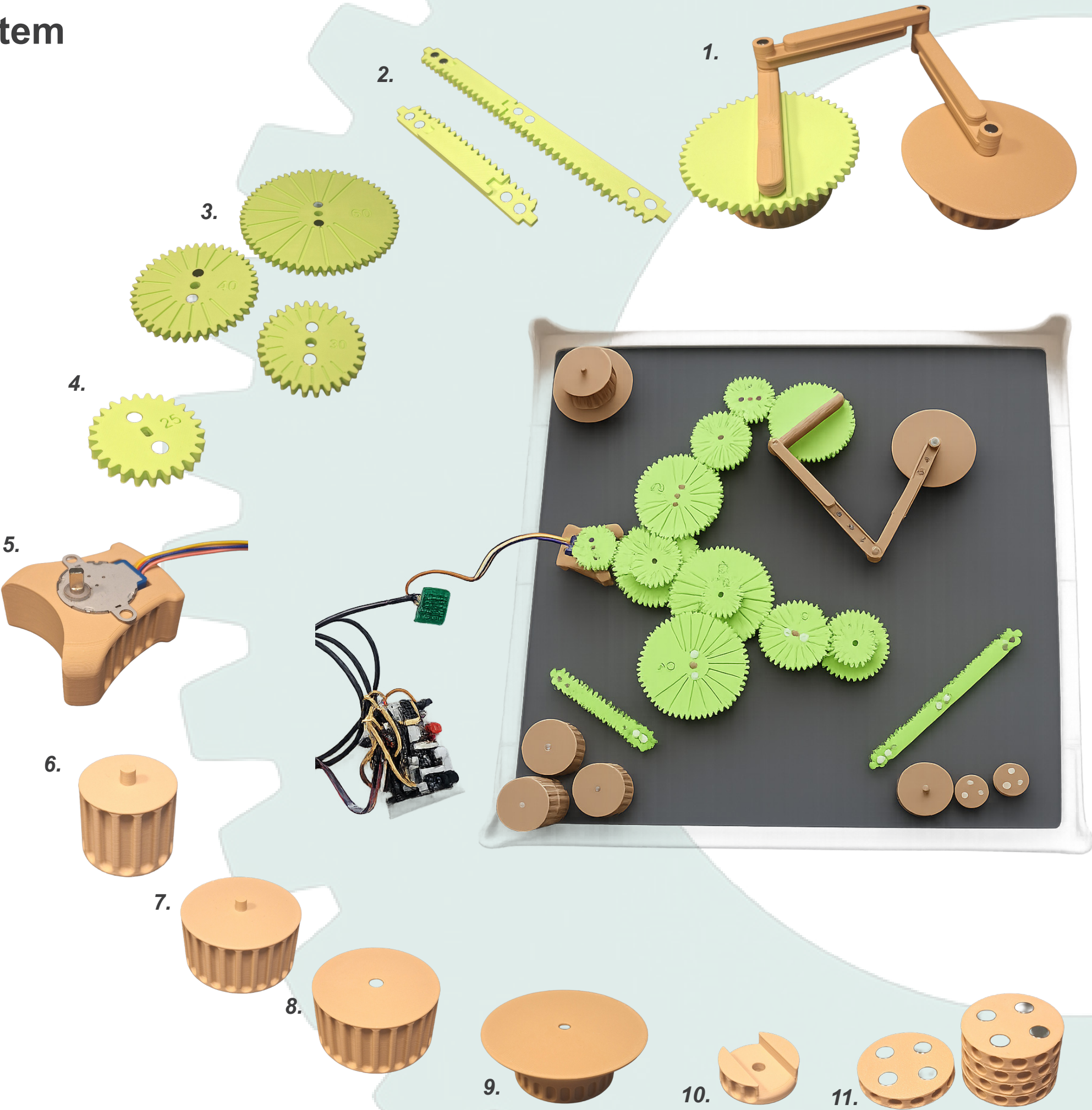


Figure 47: Physical System Components

8.3 Educational Support Systems

Several educational support systems were developed and planned to complement the physical Mechanical Garden. This chapter provides an overview of these systems and illustrates how they collectively contribute to the implementation, use, and future development of the Mechanical Garden.

The systems developed during this project include the exercise booklet, the parametric gear designer, and the programming of the control system. In addition, several supporting systems have been proposed to further expand the

functionality, scalability, and educational value of the Mechanical Garden, including an example booklet and an STL component library.

up the Mechanical Garden ecosystem. Green indicates components that are available for use. Red indicates components planned for future implementation.

Figure 48 provides an overview of the all the components and systems which make

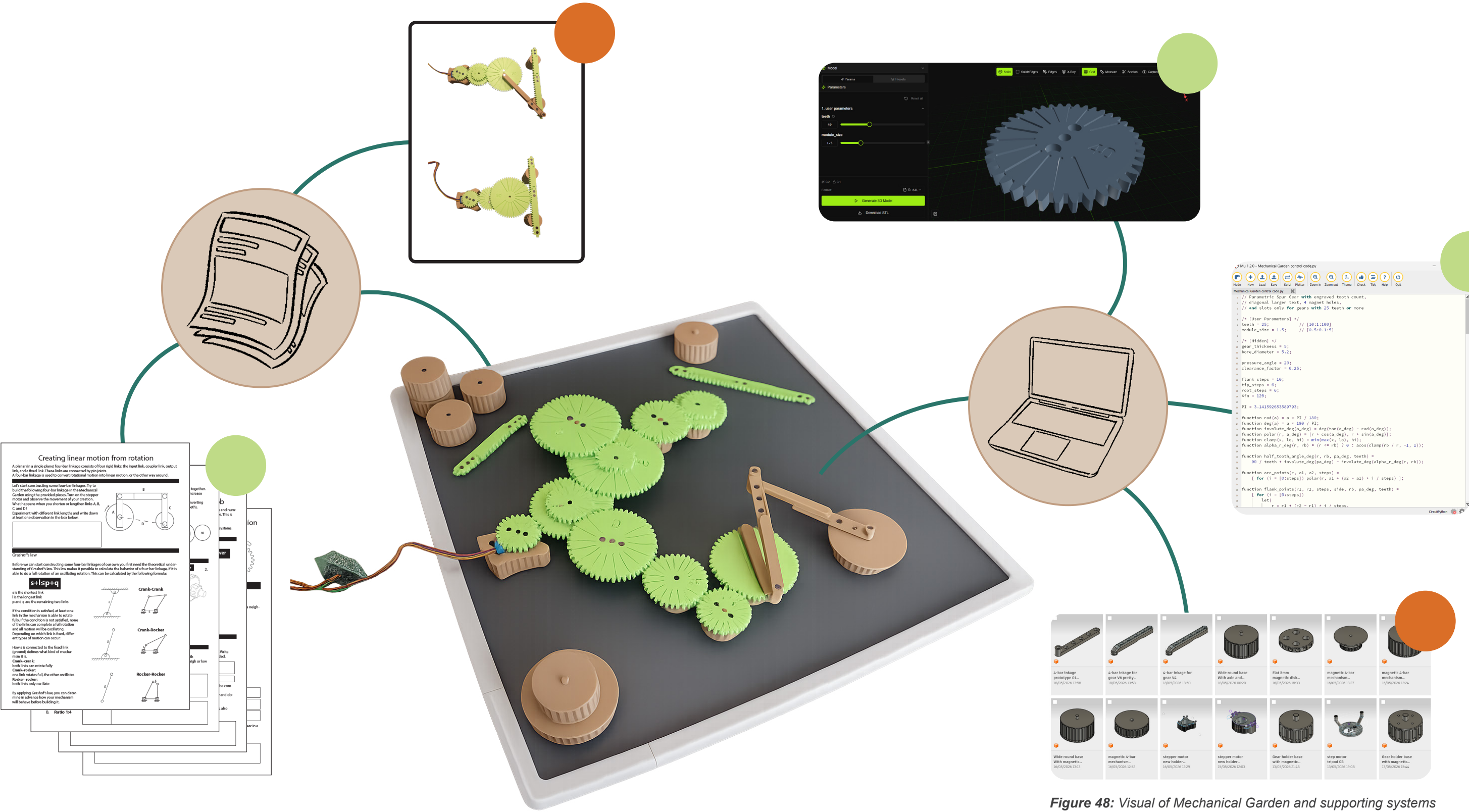
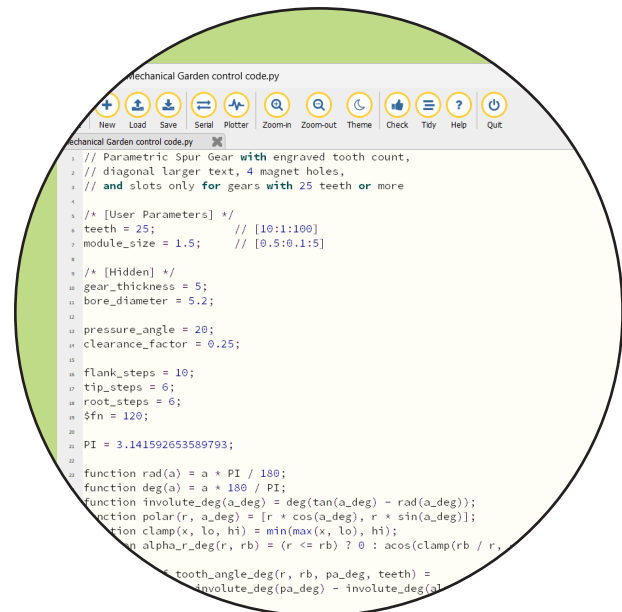
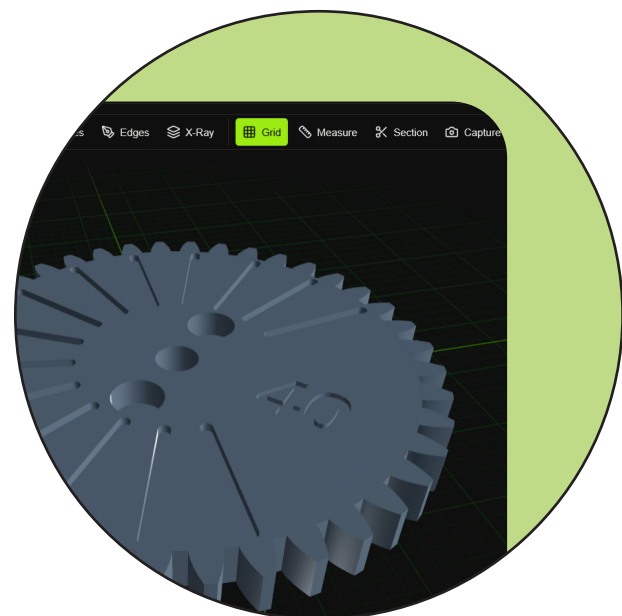


Figure 48: Visual of Mechanical Garden and supporting systems



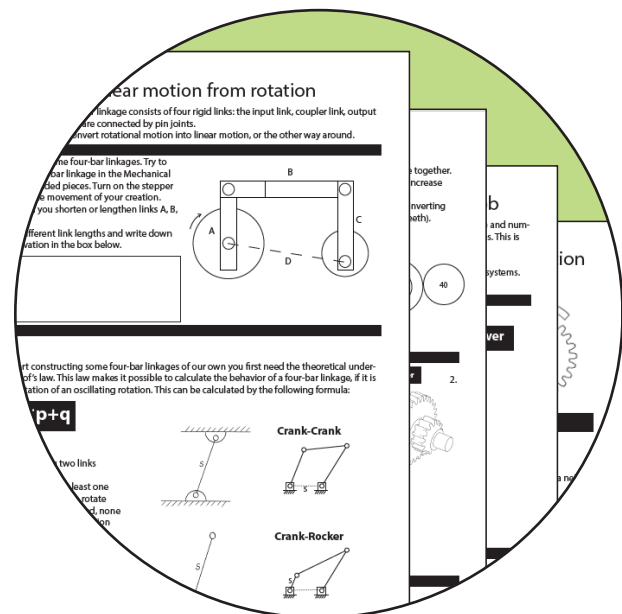
The control software developed for the Mechanical Garden is provided as Python code for the CIK. The software enables control of the motor. The code can be uploaded directly to a CIK by students or educators.

To further improve accessibility, pre-programmed CIK units could be provided, and future development could include an online repository from which users can access and download the latest version of the code.



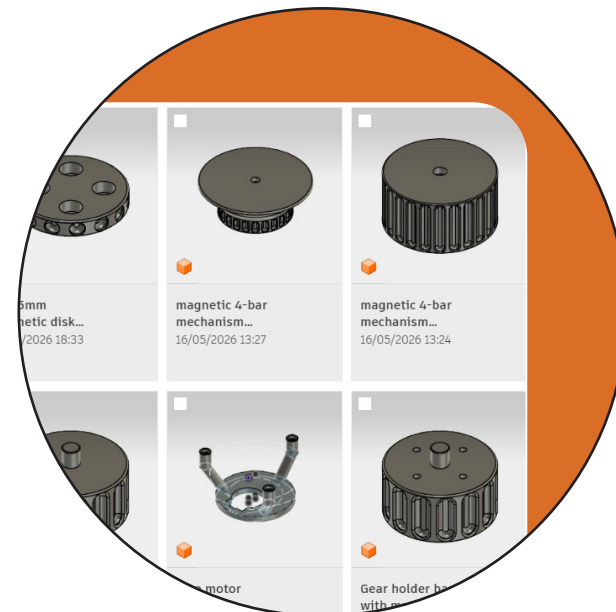
The parametric gear designer forms an important supporting component of the Mechanical Garden ecosystem. The tool has been fully developed and is currently accessible online, allowing students and educators to create custom gears for use within the system.

By enabling the creation of additional components, the gear designer supports the adaptability and long-term scalability of the Mechanical Garden.



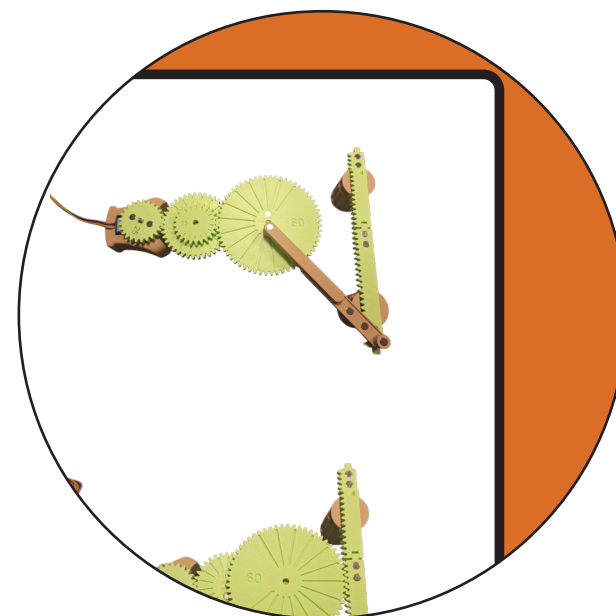
The exercise booklet was developed, iteratively refined, and evaluated throughout the project. Multiple rounds of testing with participants and educators were used to improve the content and structure of the exercises.

As part of the Mechanical Garden ecosystem, the booklet provides a validated educational component that supports the intended learning experience and can be directly implemented alongside the physical learning tool.



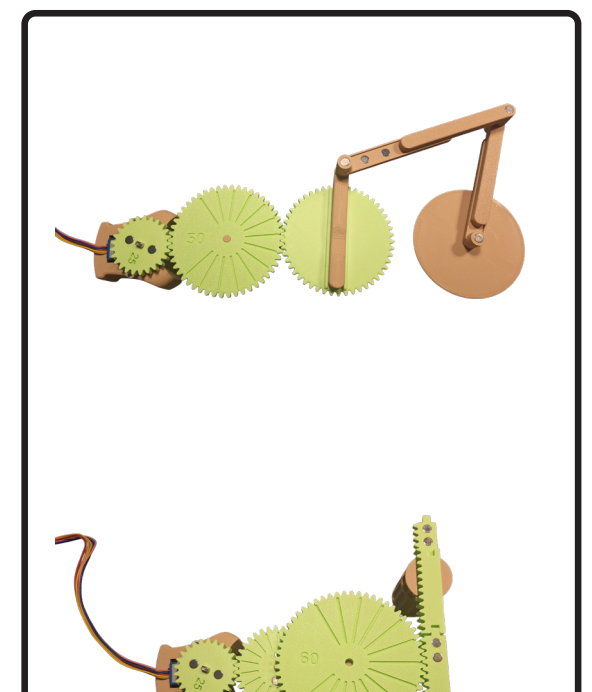
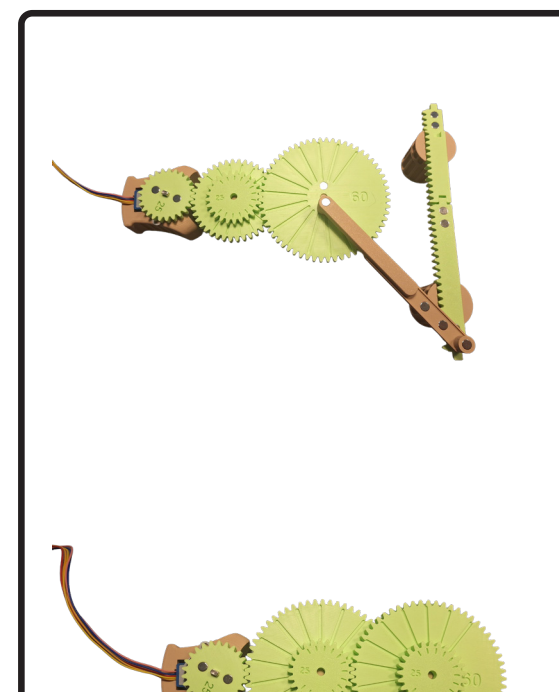
A digital STL repository is proposed as a future addition to the Mechanical Garden ecosystem. While the STL files required to manufacture the current system can already be provided directly to educators, a dedicated online repository would improve accessibility and long-term scalability.

Such a repository would allow students and educators to download component files, access updated versions, and share newly developed components. This would support the continued expansion and adaptation of the Mechanical Garden across different educational contexts.



An example booklet is proposed as a future addition to the Mechanical Garden ecosystem. The booklet would contain a collection of example mechanisms and demonstrate how these can be assembled using the Mechanical Garden components.

Such a resource could support students during exploration and provide inspiration when developing their own mechanical solutions. In addition, the booklet could assist educators in preparing educational activities and demonstrations. An example of the proposed format and content of this booklet can be found in Figure 49.



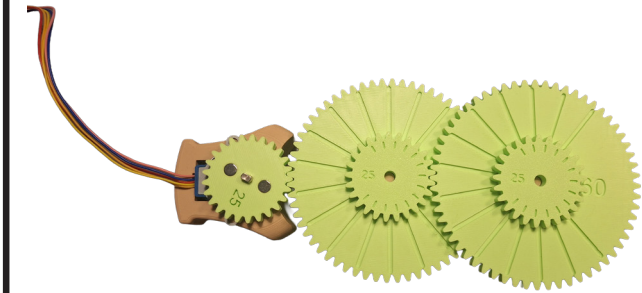
8.4 Example booklet vision

Figure 49: An example of the proposed format of example booklet



From rotations to occilating.

This mechanisms can be used to transforma rotational movement into a linear ocilating movement.



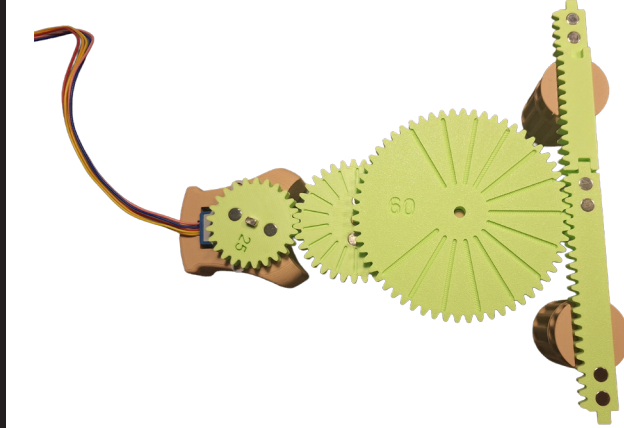
Compound gear train.

The compound gear train is able to create huge amounts of torque or speed, depending on the ratio.



Four-bar linkage.

The fourbar linkage is able to convert one type of motion into another. Continous into occilating for example.



Rack and Pinion.

The pinion (gear) interacts witht the pinion and makes it move in a linear fashion.

8.5 Mechanical Garden Carry Trolley

To support the storage and transportation of the Mechanical Garden, a standard trolley is used on which multiple Mechanical Garden units can be stored. Custom corner elements, based on the corner geometry of the building plates, are attached to the trolley.

Gardens to nest securely on top of one another during storage and transportation.

By enabling complete Mechanical Garden units to remain assembled while being stacked and transported, the trolley reduces setup and cleanup time and allows the system to be efficiently moved between storage locations and teaching spaces.

These elements allow the Mechanical



Figure 50: Pictures of storage system

8.6 Manufacturing and Assembly

The Mechanical Garden was designed to be manufactured and assembled using the facilities available at the Faculty of Industrial Design Engineering at TU Delft, Figure 51.

By relying on production methods and equipment already present within the faculty, the system can be reproduced, repaired, and expanded without requiring specialised manufacturing equipment.

The system consists of 3D-printed components, a steel build plate, electronic components, and neodymium magnets.

Additive Manufacturing

All custom components of the Mechanical Garden were manufactured using FDM 3D printing. These components include the motor mount, gear mounts, gears, stacking elements, four-bar linkage components, electronic component holders, and the build plate border. All parts were printed on a BambuLab A1 Mini using matte PLA filament with a layer height of 0.16 mm and an infill density of 15%.

To simplify production and reduce material consumption, components were specifically designed to be printed without support structures. Furthermore, most components were designed as single-part or print-in-place constructions, reducing assembly requirements and simplifying reproduction of the system (Ngo et al., 2018b).

PLA was selected as the primary manufacturing material for all custom components. Matte PLA was specifically chosen because its surface finish provides the Mechanical Garden with a clean and visually consistent appearance. The reduced visibility of layer lines contributes to a more refined and professional-looking educational product.

Build Plate

The build plate consists of a 0.8 mm thick sheet steel panel. Steel was selected because its ferromagnetic properties allow magnetic components to be positioned freely across the surface while maintaining sufficient rigidity for repeated use.

The sheet metal was cut to size using a guillotine shear available within the IDE faculty. To improve durability and provide a consistent finish, the build plate was powder coated to improve durability and provide a visually consistent finish. Powder coating was selected because it creates a durable and wear-resistant protective surface (McClements, 2025).

The build plate border consists of 3D-printed edge components designed to create a pressure-fit connection with the steel plate, allowing the assembly to be constructed without additional fasteners.

Electronic Components

The Mechanical Garden uses a stepper motor, motor driver, Adafruit ItsyBitsy microcontroller, ItsyBitsy Expander, push-buttons, and a rotary angle sensor. The stepper motor and motor driver form part of the Mechanical Garden itself, while the remaining electronic components are available in the CIK.

Assembly

Neodymium magnets are integrated into the motor mount, gear mounts, stacking elements, and four-bar linkage system. The magnets are installed using pressure-fit connections incorporated directly into the printed components.

This eliminates the need for adhesives while allowing components to be assembled quickly and replaced when necessary. If manual insertion force proved insufficient, a nylon mallet could be used to press components into position. With the exception of the powder-coating process, all manufacturing and assembly steps can be performed using equipment already available within the Faculty of Industrial Design Engineering.

This supports the practical implementation, maintenance, and future development of the Mechanical Garden within the educational environment for which it was designed.

Figure 51: PMB facility, and the 3D printers located at the facility.



8.7 Economic Feasibility & Viability

To assess the economic feasibility of implementing the Mechanical Garden within an educational environment such as the IDE Faculty, a production cost analysis was conducted. A detailed overview of the cost calculations can be found in Appendix I.

The cost calculation includes all components required to construct a single Mechanical Garden unit, including the 3D-printed components, magnets, motor, building plate, and finishing processes such as powder coating or the application of whiteboard foil. In addition, an estimate of the assembly cost was included.

Based on the manufacturing and assembly of two Mechanical Garden prototypes, it was estimated that approximately one to two hours are required to assemble a single Mechanical Garden unit.

Table 5 presents the estimated production costs of the Mechanical Garden. Depending on the selected finishing method, the total production cost ranges from **€34.67** for an untreated building plate to **€48.30** for a powder-coated version. The estimated cost of the powder-coated version is based on a quotation provided by PCW Poedercoat Westland for a production batch of 100 units. Applying whiteboard foil results in a total production cost of **€35.47** per unit.

The Dutch minimum wage as of 1 July 2026 is €14.99 per hour (Ministerie van Algemene Zaken, 2026b). Assuming an assembly time of approximately two hours, an additional labour cost of €29.98 per unit should be considered when the Mechanical Garden is assembled by paid

personnel.

Alternatively, assembly could be integrated into educational activities or workshops, allowing students to assemble the Mechanical Garden units themselves prior to use. Besides reducing labour costs, this approach may also familiarise students with the individual components and construction principles of the system.

The majority of the production cost originates from the building plate, magnets, and finishing process, while the cost of the 3D-printed components remains relatively low. In total, the Mechanical Garden requires approximately 335 g of Latte Brown filament, 194 g of Apple Green filament, and 287 g of Bone White filament.

The relatively low production cost suggests that multiple Mechanical Garden units could be manufactured for educational deployment. For comparison, educational construction kits such as LEGO Spike Prime are available at a retail price of approximately €469.40 per set (BV RATO EDUCATION, n.d.). While the two systems differ in functionality, this comparison illustrates that the Mechanical Garden can be produced at a substantially lower cost.

Furthermore, the majority of the components can be reproduced using standard FDM 3D printers, allowing damaged or missing parts to be replaced without requiring specialised manufacturing processes.

From an economic perspective, the Mechanical Garden appears feasible

for implementation within educational manufacturing methods enables the settings. The combination of relatively production of multiple units suitable for low production costs, reproducible classroom use. components, and accessible

Table 5: Cost of mechanical garden exlusing and including labour cost

Mechanical Garden version	Price (Excluding labour)	Price (Including labour (2 hours))
Powder coated building plate	€ 48,30	€ 78,28
White board maker foil building plate	€ 35,47	€ 65,45
Untreated building plate	€ 34,67	€ 64,65

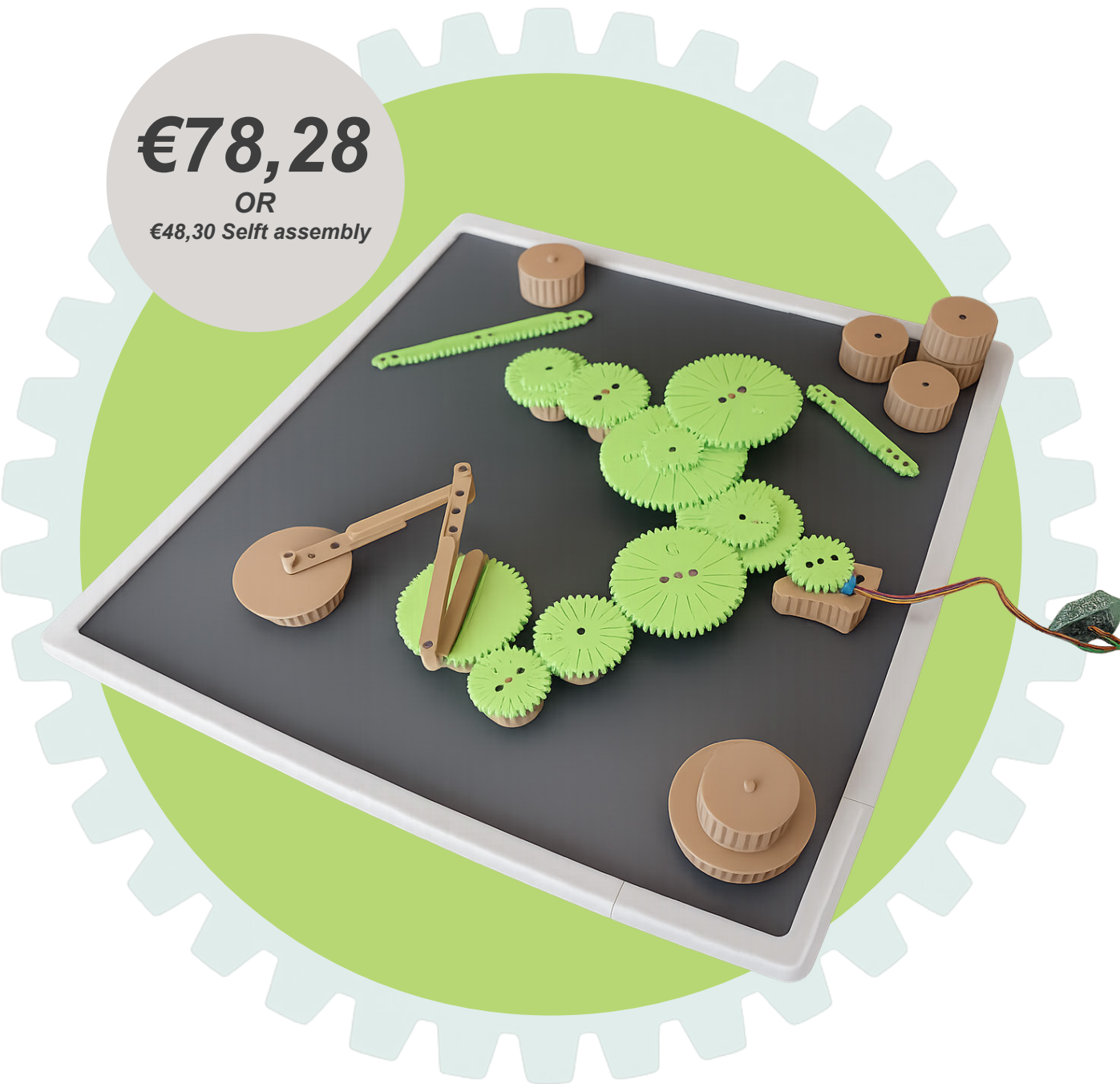
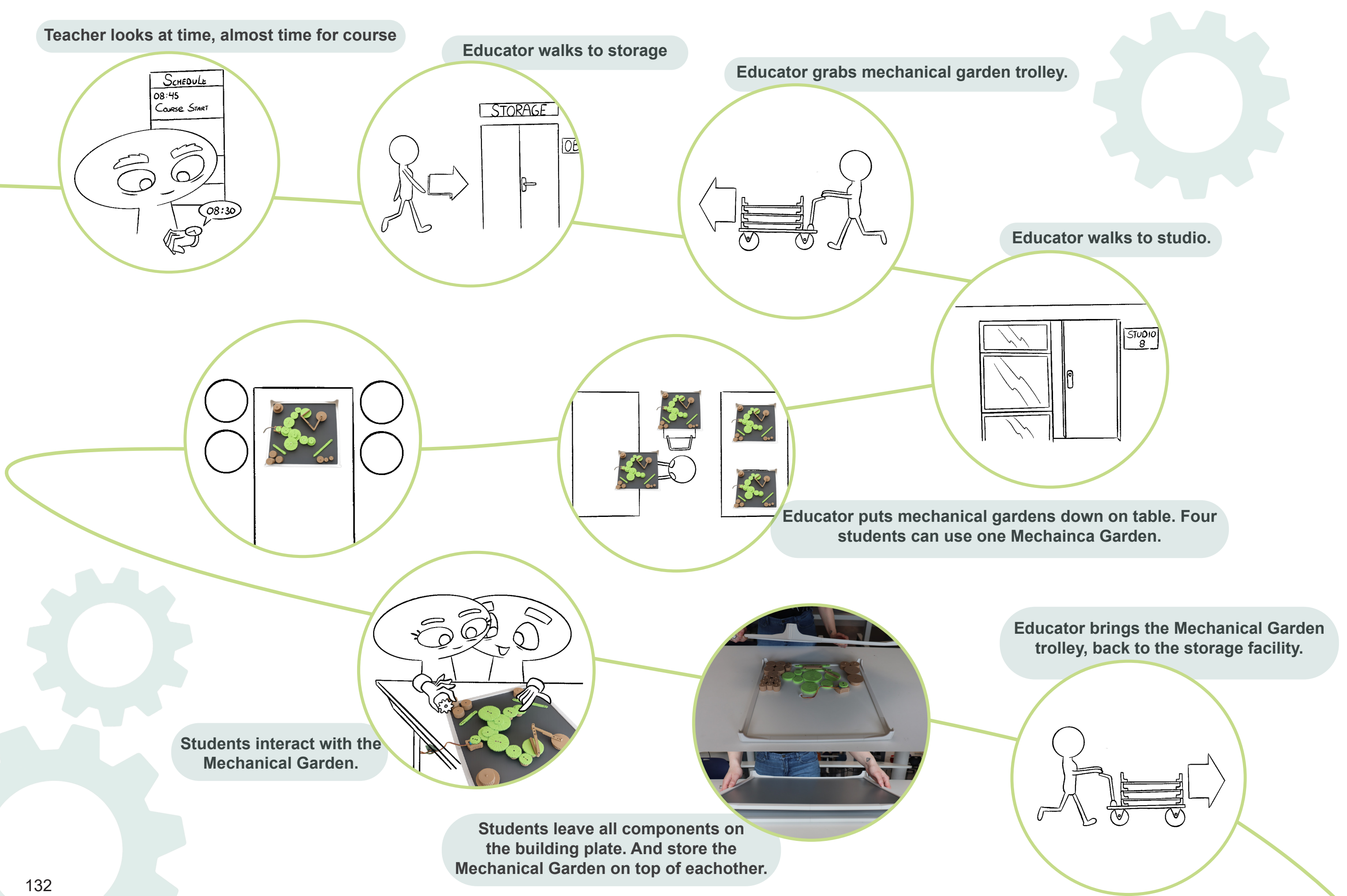


Figure 52: Cost poster of Powder coated Mechanical Garden.

8.8 Product Journey

Figure 48: Visual story of product journey



8.9 Course Implementation

Following discussions with DP3 educators, it was determined that the Mechanical Garden would be most suitable for implementation as a workshop early in the DP3 course.

During this workshop, students are introduced to the Mechanical Garden and provided with access to the physical construction system, the exercise booklet, and the Python control software for the CIK, enabling them to control the stepper motor and interact with the system.

The workshop would be facilitated by studio coaches, who would guide students through the learning activities and support experimentation where necessary. Students would work through the exercises included in the booklet, which introduce concepts such as gear rotation direction, gear ratios, compound gears, and four-bar linkages.

The workshop concludes with a design challenge in which students

apply the acquired knowledge to construct a mechanical gripper. The complete workshop is expected to take approximately four hours.

Implementing the Mechanical Garden early in the course allows students to develop an understanding of fundamental mechanical principles before these concepts are required within their design projects a visual representation of where in a course such as DP3 the Mechanical Garden could be implemented is shown in Figure 49.

As a conceptual learning tool, the Mechanical Garden is intended to help students explore, visualise, and experiment with mechanical concepts through physical interaction. By constructing, testing, and modifying mechanisms, students are provided with opportunities to gain hands-on experience with concepts that were previously identified as challenging by both educators and students.

The workshop also provides students with exposure to a variety of mechanical principles and mechanisms that can later be applied within their own design projects. This may support students in identifying technically feasible solutions, exploring different approaches to movement, and making more informed design decisions during the development of their robotic systems.

Following the workshop, students would be able to continue using the Mechanical Garden throughout the remainder of the course. This would allow them to prototype, test, and evaluate mechanical solutions developed as part of their design projects. Rather than functioning solely as an introductory learning activity, the Mechanical Garden would remain available as a prototyping and experimentation platform that supports the development, exploration, and validation of mechanical concepts throughout DP3.

The knowledge and experience gained during the workshop is expected to contribute to more focused and effective prototyping activities throughout the remainder of the course.

By becoming familiar with common mechanical principles and mechanisms early in the design process, students are may be better equipped to evaluate potential solutions and select appropriate mechanisms for their projects. This would enable students to develop more technically informed, complex, and purposeful prototypes while making more effective use of the limited time available during the course.

By combining conceptual learning, hands-on experimentation, and continued access throughout the course, the Mechanical Garden has the potential to support both the understanding and practical application of mechanical principles within the DP3 curriculum.

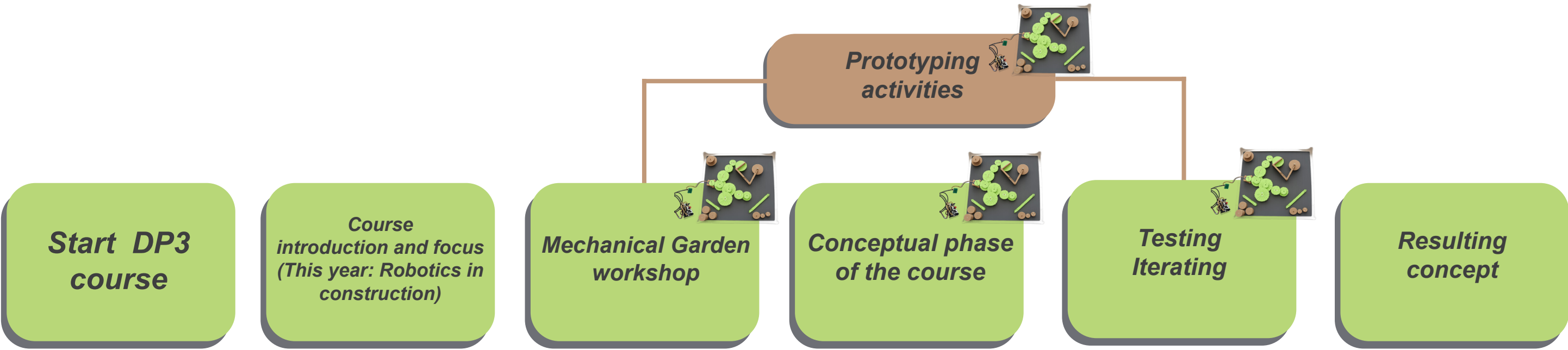
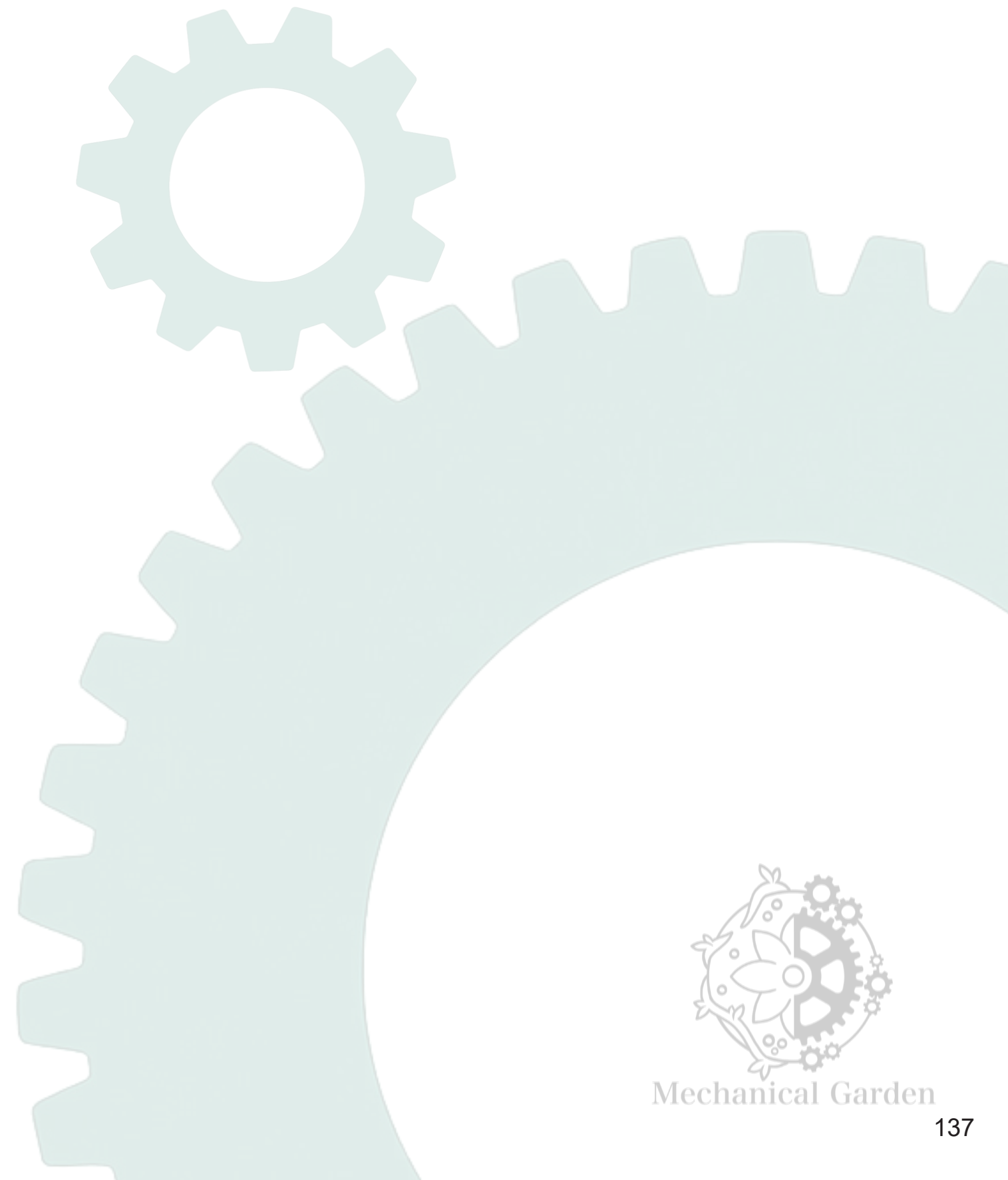


Figure 49: Visual representation of implementing Mechanical in a course. with DP3 as example.

Chapter 9.

Future work

The Mechanical Garden demonstrated promising educational potential, yet several opportunities exist for further validation, expansion, and implementation of the system. The following sections outline possible directions for future work.



9.1 Educational Validation

The first priority for future work should be the implementation and evaluation of the Mechanical Garden within the DP3 course. While the current evaluation demonstrated improvements in participants' understanding of mechanical principles, the educational impact of the Mechanical Garden has not yet been investigated within its intended educational context.

A future study could compare two groups of students, a control group following the existing DP3 curriculum and an experimental group using the Mechanical Garden throughout the course. Following completion of the course, the quality, technical complexity, and feasibility of the developed prototypes could be assessed by multiple educators to determine whether interaction with the Mechanical Garden results in improved mechanical solutions within student projects.

In addition, students' understanding and application of mechanical principles could be evaluated to determine whether the acquired knowledge transfers to new design problems and is retained throughout the course.

Future research could also investigate which aspects of the Mechanical Garden contribute most to learning. For example, the influence of physical interaction, experimentation, repeated iteration, and guided exercises could be studied individually to better understand how each contributes to conceptual understanding and the application of mechanical principles.

9.2 Technical Expansion

Following successful validation, the Mechanical Garden could be further expanded through the development of additional components and supporting systems.

One potential addition is a rotational speed measurement module capable of displaying the rotational speed (RPM) of individual gears. Such a component would allow students to compare theoretical calculations with measured values and investigate real-world engineering problems within the Mechanical Garden environment.

Additional construction components could further increase the range of mechanical principles that can be explored. For example, vertical building plates could enable the construction of cam mechanisms and other three-dimensional assemblies.

Similarly, new modules for mechanisms such as ratchets, Geneva drives, and other commonly used mechanical systems could broaden the educational capabilities of the Mechanical Garden and expose students to a wider variety of engineering solutions.

The existing parametric gear designer could also be expanded to support additional gear types, including worm gears and herringbone gears. This would further increase the versatility of the Mechanical Garden while allowing students to continue manufacturing custom components using the existing workflow.

The accompanying exercise booklet should continue to evolve through additional testing and iterative refinement.

New exercises could introduce increasingly complex mechanisms and design challenges while supporting a broader range of learning objectives. In addition, a compact reference booklet containing commonly used formulas, mechanical principles, and example mechanisms could be developed to provide students with a readily accessible theoretical reference during experimentation and project work.

9.3 Scalability and Future Implementation

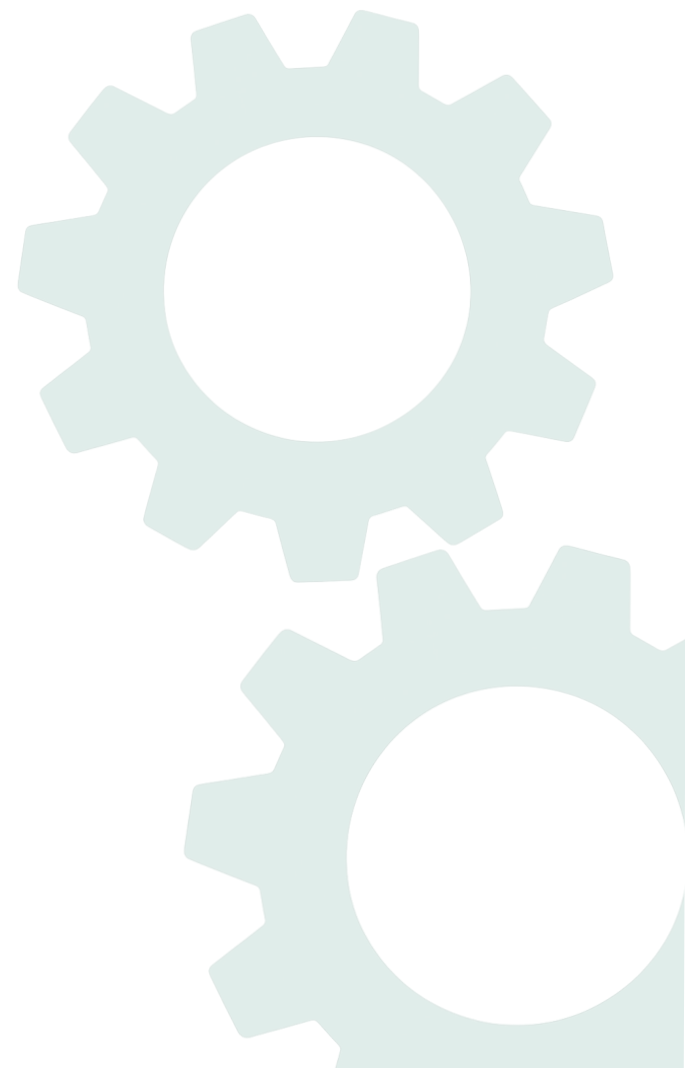
Beyond the DP3 course, the Mechanical Garden could be implemented within a broader range of educational settings. Discussions with educators identified the potential for a dedicated demonstration version that could be used during lectures to illustrate mechanical principles before students begin experimenting independently.

Such a demonstrator would allow educators to integrate physical examples into existing teaching activities and visually introduce mechanical concepts to larger groups of students.

Future work could also investigate the applicability of the Mechanical Garden within other courses, faculties, universities, and educational levels. Introducing students to mechanical principles through physical interaction at an earlier stage of their education may strengthen their conceptual understanding before they encounter more complex engineering and design challenges in higher education.

Finally, the Mechanical Garden ecosystem could continue to develop through the expansion of its digital support systems. A digital STL repository containing printable components, replacement parts, and newly developed modules would allow educators and students to continuously reproduce, repair, and expand the system.

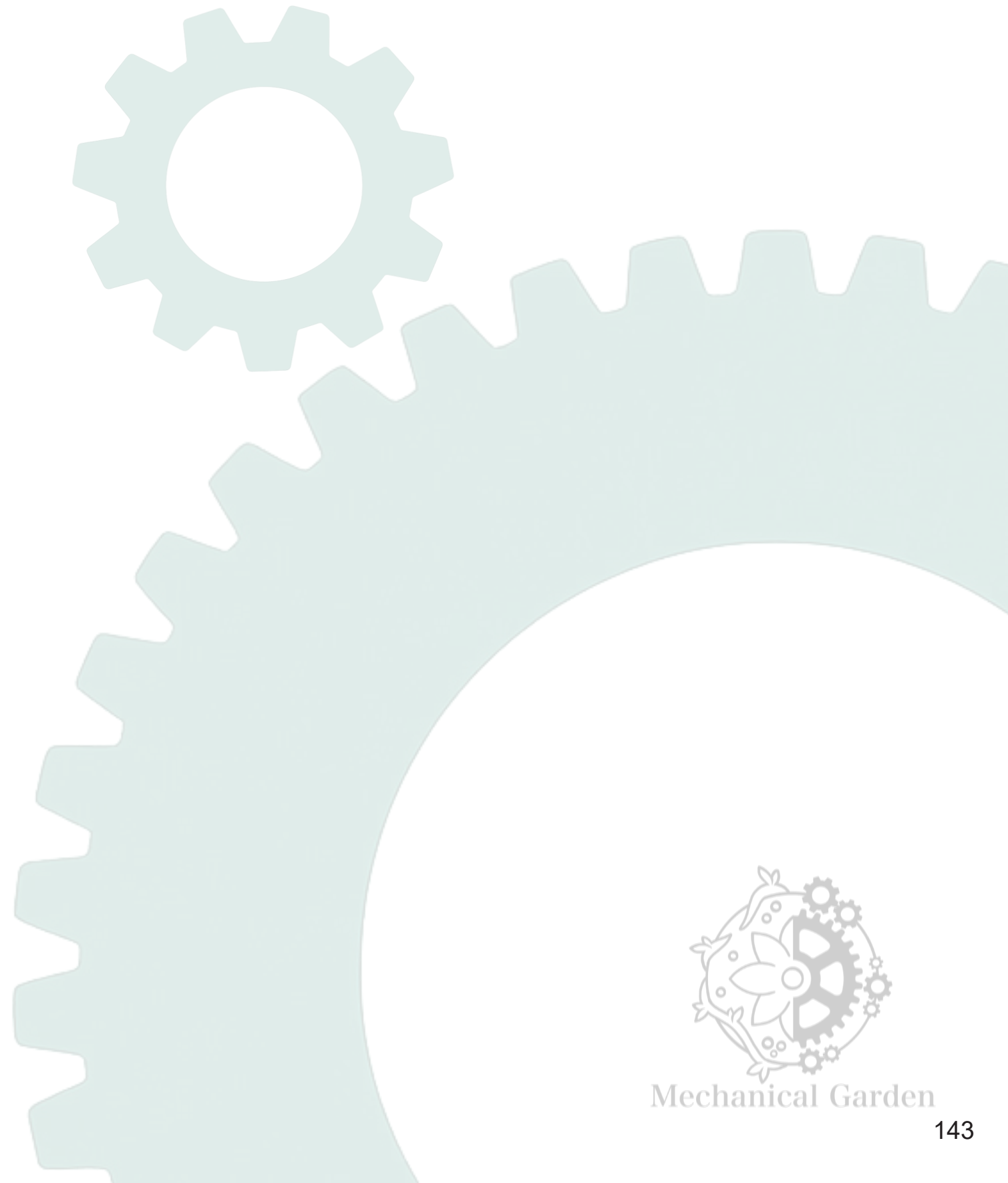
Combined with the parametric gear designer and future component libraries, this approach would enable the Mechanical Garden to evolve into a scalable educational platform that can be maintained and further developed over time by both educators and students.



Chapter 10.

Conclusion

The following chapter will provide a conclusion of the entire project.



This graduation project investigated how a tangible conceptual learning tool can support Industrial Design Engineering students in moving from abstract knowledge towards a more intuitive understanding of mechanical principles. The project originated from observations, educator interviews, and literature, which consistently indicated that students experience difficulties translating theoretical mechanical knowledge into practical design solutions.

Throughout the iterative Research-through-Design process, it became clear that simply presenting students with mechanical examples was insufficient to support deeper understanding. The project therefore gradually evolved from introducing mechanisms through passive interaction towards the development of a complete learning ecosystem that combines physical construction, guided exercises, digital tools, and open-ended experimentation. This resulted in the Mechanical Garden: a conceptual learning tool designed to support exploration, experimentation, and the practical application of mechanical principles.

The evaluation demonstrated promising educational potential. Participants improved their average score from 54% on the pre-test to 91% on the post-test, representing an average improvement of 37 percentage points. In addition, participants positively evaluated the Mechanical Garden, indicating that it helped them better understand mechanical principles, encouraged active experimentation, and could be a valuable addition to the DP3 curriculum.

The main research question of this thesis was: *How can a tangible conceptual learning tool support Industrial Design*

Engineering students in moving from abstract knowledge towards a more intuitive understanding of mechanical principles? Based on the findings of this research, this question can be answered by stating that a tangible conceptual learning tool supports learning by enabling students to actively construct, manipulate, test, and evaluate mechanical systems while receiving immediate visual feedback.

By combining physical interaction with guided exercises and opportunities for open-ended experimentation, theoretical concepts become directly observable, allowing students to develop a deeper conceptual understanding and apply this knowledge within a design context.

The sub-research questions demonstrated that students particularly struggle with applying mechanical principles during design projects, that existing educational methods provide limited opportunities for active experimentation, that physical interaction plays an important role in developing conceptual understanding, and that learning tools should combine educational guidance with the freedom to explore and construct mechanisms independently.

The main contribution of this project is therefore not only the development of the Mechanical Garden itself, but also the demonstration that combining tangible interaction, guided learning, and productive failure can support students in developing a deeper understanding of mechanical principles. Rather than functioning solely as a construction kit, the Mechanical Garden provides an educational ecosystem that bridges the gap between theoretical instruction and practical application.

Furthermore, the estimated production cost of €35–48 (€65–78 including assembly labour costs) per Mechanical Garden unit demonstrates that the system is economically feasible for implementation within educational environments and enables the deployment of multiple units for classroom use.

Overall, this project demonstrates the potential of tangible conceptual learning tools to support engineering education through active experimentation and immediate visual feedback. Although further validation within the DP3 curriculum is recommended, the findings suggest that the Mechanical Garden provides a promising approach for improving the teaching, learning, and application of mechanical principles within engineering and design education.

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Appendix

- Appendix A - Important take aways interviews
- Appendix B - Student survey/questionnaire (perceived difficulty)
- Appendix C - Research template building board size
- Appendix D - Research template magnetism
- Appendix E - CIK Controller Python code
- Appendix F - Excersize booklet
- Appendix G - Scriptsolid code gear designer
- Appendix H - Perceived usefullness questionnaire
- Appendix I - Bill of materials

Appendix A Important take aways interviews

Educator 1
Practical, build-based learning works best, but has become more difficult due to the large number of students.

The absence of clear technical learning pathways within Industrial Design results in fragmented knowledge.

Well-designed assignments are the foundation of effective education and directly connect theory to hands-on experimentation.

Building and investigating together with students increases motivation and a sense of responsibility.

Productive failure—learning through making mistakes—leads to deeper technical understanding.

Small groups provide the highest quality education and the strongest student engagement.

Educator 2
Fundamental concepts related to vectors are perceived as difficult, particularly by international students.

Students struggle to understand what vectors can be used for and how they are relevant within the design process.

The cross product (moment in 3D) is considered difficult, both conceptually and in its application.

Students often forget that forces and structural members can be represented as vectors, providing insight into moments.

Physically representing and decomposing moments in both 2D and 3D remains a major challenge.

Technical drawing causes difficulties, particularly regarding dimensions, tolerances, and the “language” of technical specifications.

Knowledge of manufacturing methods and how they influence design decisions has largely disappeared.

Machine Design & Detailing (MDD) has mostly disappeared from the curriculum, resulting in students lacking a technical foundation.

Students struggle to define technical specifications clearly enough for manufacturing to produce components accurately.

Due to limited exposure, students rarely encounter engineering and manufacturing principles.

Educator 3

How people learn scientific concepts most effectively

Information should be revisited regularly (interleaving) to be retained in long-term memory.

The forgetting curve demonstrates that one-time instruction does not result in lasting knowledge.

Retrieval practice—actively recalling knowledge—is essential for long-term retention.

Students learn most effectively when they are allowed to make mistakes (productive failure) before receiving the correct explanation.

Learning is more effective when students are encouraged through curiosity rather than control or performance pressure.

Understanding develops when cognitive knowledge is combined with experience (implicit and explicit knowledge).

Knowledge only becomes true understanding when students can transfer and apply it within their own context.

Scientific concepts within a learning pathway

Concepts should be repeated and consistently developed throughout the curriculum rather than being taught in a single course.

Educators within the same learning pathway should better align their teaching to ensure continuity.

An excessive focus on short-term cramming for examinations weakens the understanding of fundamental principles.

The role of context in learning

Context activates abstract concepts and makes them understandable and relevant.

A well-designed learning environment stimulates curiosity and experimentation.

Practical setups (such as mechanics demonstrations or machines) help students physically experience scientific principles.

A community-like environment (interaction, collaboration, shared learning) improves long-term retention.

The right environment creates entropy: increasing opportunities for ideas and people to meet, resulting in more learning.

Students learn more effectively when the environment allows them to experiment, fail, try again, and only receive feedback afterwards.

Educator 4

A weak foundation in algebra makes it difficult for students to understand and correctly apply physics concepts.

Difficulties with rearranging equations, differentiation, and integration limit understanding of motion, velocity, position, and forces.

Students often fail to recognize when calculated forces are physically impossible due to a lack of intuitive understanding of scale and order of magnitude.

Many students do not spontaneously apply theoretical concepts in new contexts (e.g., FEA, thermal, or fluid simulations).

Calculation-based assessments often result in errors caused by inaccurate calculations, careless mathematical steps, and cumulative numerical errors.

Differential equations are conceptually difficult, even when students solve them using code.

Programming assignments are challenging because students often use code without understanding the underlying concepts or algorithms.

Excessive use of ChatGPT results in code that functions correctly but is not understood, limiting conceptual learning.

Students find it difficult to build prototypes.

Students remain in the design studios instead of going to the workshop.

Students find it difficult to apply the knowledge they have learned to their own designs.

Scientific concepts identified as difficult

- Vectors (definition, application in design, representing forces as vectors)
- Cross product (moment in 3D)
- Moment / bending moment
- Resolving moments into components (2D and 3D)
- Beam curvature (1/r relationship with bending moment)
- Using rods/fibres on a beam to visualize stresses
- Internal stress – relationship with visible deformation
- Strength of materials (stress–strain behaviour, material response)
- Statics principles (equilibrium, forces, moments)
- Elasticity
- Deformation of MDF / beam experiments
- Structural mechanics within the design process

Scientific principles and difficulties

Hoe moeilijk vind je de volgende mechanische en natuurkundige principes?

Geef per onderwerp aan hoe moeilijk jij dit principe vindt op basis van je ervaring tijdens de studie Industrieel Ontwerpen. Er zijn geen goede of foute antwoorden.

1. **Krachten (Newton)**
een duw of trek die de beweging of vorm van een voorwerp kan veranderen.

Mark only one oval.

12345

Heel gemakkelijk☐ ☐ ☐ ☐ ☐ Heel moeilijk

2. **Momenten**
het draaiend effect van een kracht rond een draaipunt.

Mark only one oval.

12345

Heel gemakkelijk☐ ☐ ☐ ☐ ☐ Heel moeilijk

3. **Evenwichten**

een toestand waarin alle krachten en momenten elkaar opheffen, zodat een voorwerp in rust blijft of constant beweegt.

Mark only one oval.

	1	2	3	4	5	
Heel	☐	☐	☐	☐	☐	Heel moeilijk

4. **Hefbomen**

een hulpmiddel waarbij een kleine kracht een grotere kracht kan vervangen door gebruik te maken van een draaipunt en een arm.

Mark only one oval.

	1	2	3	4	5	
Heel	☐	☐	☐	☐	☐	Heel moeilijk

5. **Degrees of freedom**

het aantal onafhankelijke manieren waarop een voorwerp kan bewegen of draaien.

Mark only one oval.

	1	2	3	4	5	
Heel	☐	☐	☐	☐	☐	Heel moeilijk

6. **Druk en spanning**

druk is de kracht per oppervlakte-eenheid die op een oppervlak werkt, terwijl spanning de kracht is die binnenin een materiaal wordt overgedragen.

Mark only one oval.

	1	2	3	4	5	
Heel	☐	☐	☐	☐	☐	Heel moeilijk

7. **Rek, elasticiteit, plastisch gedrag**

rek is de relatieve verlenging van een materiaal, elasticiteit betekent dat het materiaal terugkeert naar zijn oorspronkelijke of andere vorm, en plastisch gedrag dat de vervorming blijvend is.

Mark only one oval.

	1	2	3	4	5	
Heel	☐	☐	☐	☐	☐	Heel moeilijk

8. **Traagheid/massa-inertie**

de eigenschap van een massa om weerstand te bieden tegen veranderingen in zijn beweging.

Mark only one oval.

	1	2	3	4	5	
Heel	☐	☐	☐	☐	☐	Heel moeilijk

9. **Wrijving**

een kracht die de relatieve beweging tussen twee contactoppervlakken tegenwerkt.

Mark only one oval.

	1	2	3	4	5	
Heel	☐	☐	☐	☐	☐	Heel moeilijk

10. **Torsie**

torsie is het verdraaien van een object door een moment.

Mark only one oval.

	1	2	3	4	5	
Heel	☐	☐	☐	☐	☐	Heel moeilijk

11. **Buiging**

het vervormen van een voorwerp doordat er een kracht of moment loodrecht op de lengte werkt, waardoor het krom trekt.

Mark only one oval.

	1	2	3	4	5	
Heel	☐	☐	☐	☐	☐	Heel moeilijk

12. **Veerkracht**

de kracht waarmee een veer of elastisch materiaal terug wil keren naar zijn oorspronkelijke vorm na vervorming.

Mark only one oval.

	1	2	3	4	5	
Heel	☐	☐	☐	☐	☐	Heel moeilijk

13. **Versnelling**

de verandering van snelheid per tijdseenheid.

Mark only one oval.

	1	2	3	4	5	
Heel	☐	☐	☐	☐	☐	Heel moeilijk

14. **Trillingen/resonantie**

trillingen zijn herhaalde bewegingen rond een evenwichtsstand, en resonantie treedt op wanneer een systeem extra sterk gaat trillen bij zijn eigen frequentie.

Mark only one oval.

	1	2	3	4	5	
Heel	☐	☐	☐	☐	☐	Heel moeilijk

15. **Translatie en Rotatie**

translatie is beweging zonder draaien waarbij alle punten even ver verschuiven, en rotatie is beweging waarbij een voorwerp draait rond een as.

Mark only one oval.

	1	2	3	4	5	
Heel	☐	☐	☐	☐	☐	Heel moeilijk

16. **Snelheid/versnelling**

snelheid is hoe snel en in welke richting een voorwerp beweegt, en versnelling is hoe snel die snelheid verandert.

Mark only one oval.

	1	2	3	4	5	
Heel	☐	☐	☐	☐	☐	Heel moeilijk

17. **Impuls en momentum**

*Momentum geeft aan hoe moeilijk het is om een bewegend voorwerp te stoppen.
Impuls beschrijft hoeveel de kracht een beweging verandert in een bepaalde tijd.*

Mark only one oval.

	1	2	3	4	5	
Heel	☐	☐	☐	☐	☐	Heel moeilijk

18. **Traagheids moment**

een maat voor hoe moeilijk het is om een voorwerp in rotatie te versnellen of af te remmen rond een bepaalde as.

Mark only one oval.

	1	2	3	4	5	
Heel	☐	☐	☐	☐	☐	Heel moeilijk

19. **Mechanismen**

systemen van verbonden onderdelen die beweging of kracht overbrengen en omzetten.

Mark only one oval.

	1	2	3	4	5	
Heel	☐	☐	☐	☐	☐	Heel moeilijk

20. **Vakwerken**

constructies van staven die via knooppunten verbonden zijn en krachten vooral als trek en druk doorgeven.

Mark only one oval.

	1	2	3	4	5	
Heel	☐	☐	☐	☐	☐	Heel moeilijk

21. **Tandwielen en pulley's**

systemen die beweging en kracht overbrengen en aanpassen door rotatie of via een riem of ketting.

Mark only one oval.

1 2 3 4 5

Heel ☐ ☐ ☐ ☐ ☐ Heel moeilijk

22. **Hoeksnelheid**

de snelheid waarmee een voorwerp draait, uitgedrukt als hoekverandering per tijdseenheid.

Mark only one oval.

1 2 3 4 5

Heel ☐ ☐ ☐ ☐ ☐ Heel moeilijk

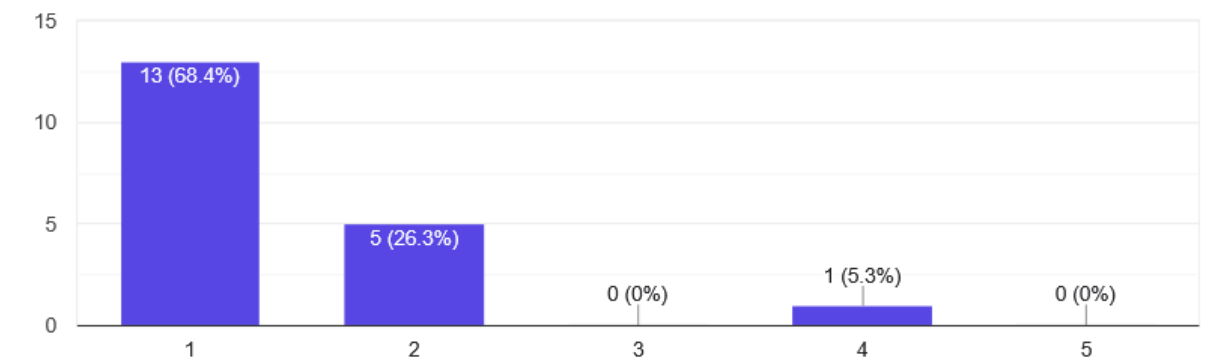
23. **Andere concepten waarmee je moeite hebt gehad tijdens de studie die niet in deze questionnaire staan.**

Krachten (Newton)

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een duw of trek die de beweging of vorm van een voorwerp kan veranderen.

19 responses

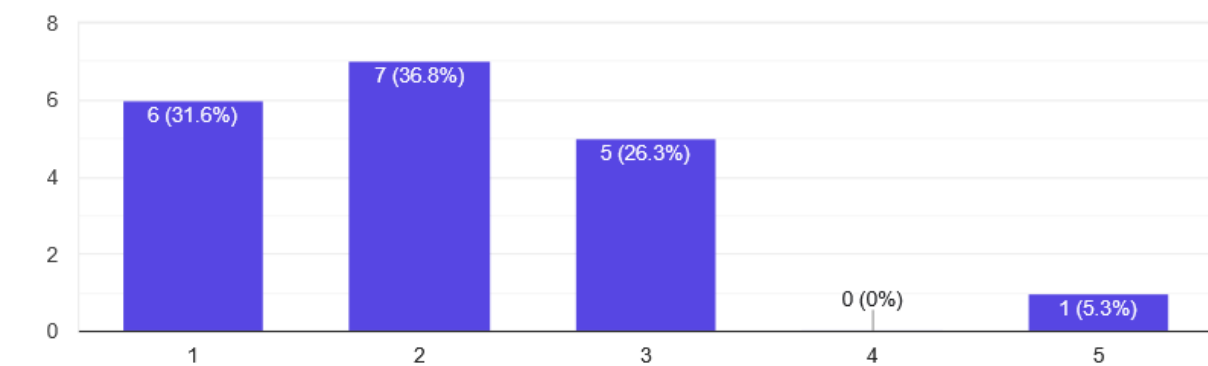


Momenten

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het draaiend effect van een kracht rond een draaipunt.

19 responses

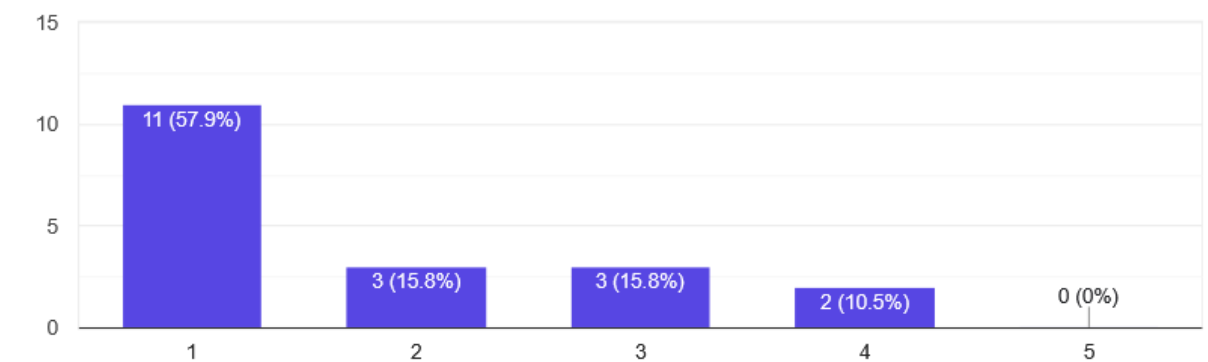


Evenwichten

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een toestand waarin alle krachten en momenten elkaar opheffen, zodat een voorwerp in rust blijft of constant beweegt.

19 responses

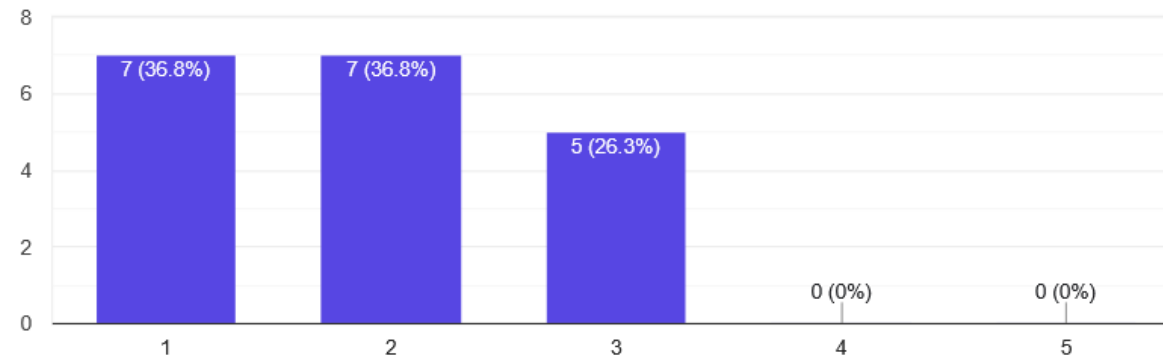


Hefbomen

een hulpmiddel waarbij een kleine kracht een grotere kracht kan vervangen door gebruik te maken van een draaipunt en een arm.

19 responses

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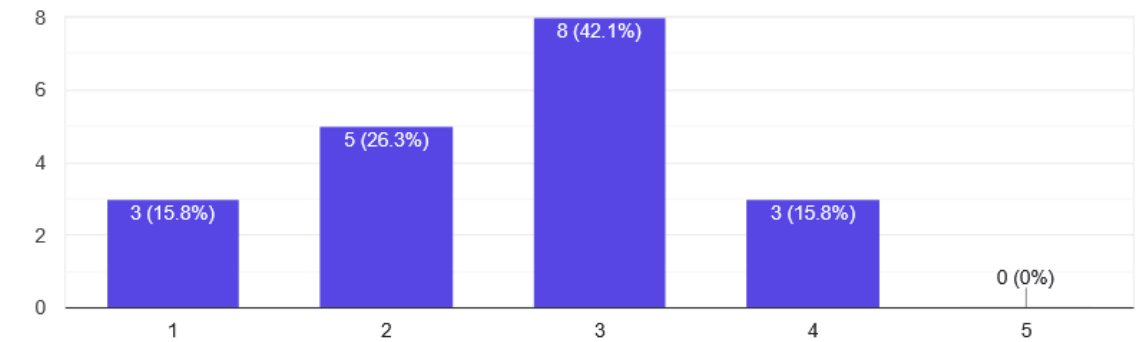


Rek, elasticiteti, plastisch gedrag

rek is de relatieve verlenging van een materiaal, elasticiteit betekent dat het materiaal terugkeert naar zijn oorspronkelijke of andere vorm, en plastisch gedrag dat de vervorming blijvend is.

19 responses

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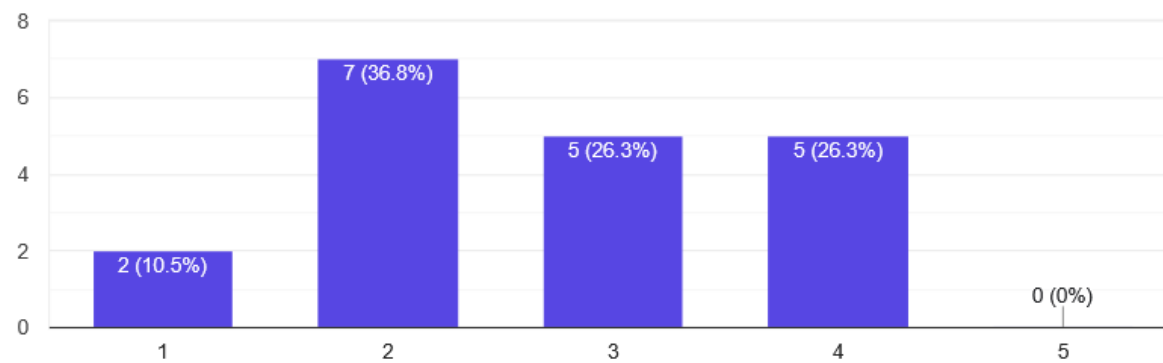


Degrees of freedom

het aantal onafhankelijke manieren waarop een voorwerp kan bewegen of draaien.

19 responses

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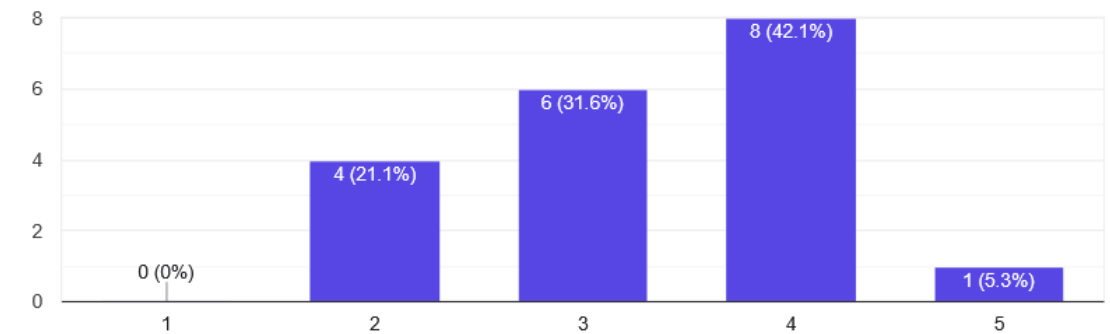


Traagheid/massa-inertie

de eigenschap van een massa om weerstand te bieden tegen veranderingen in zijn beweging.

19 responses

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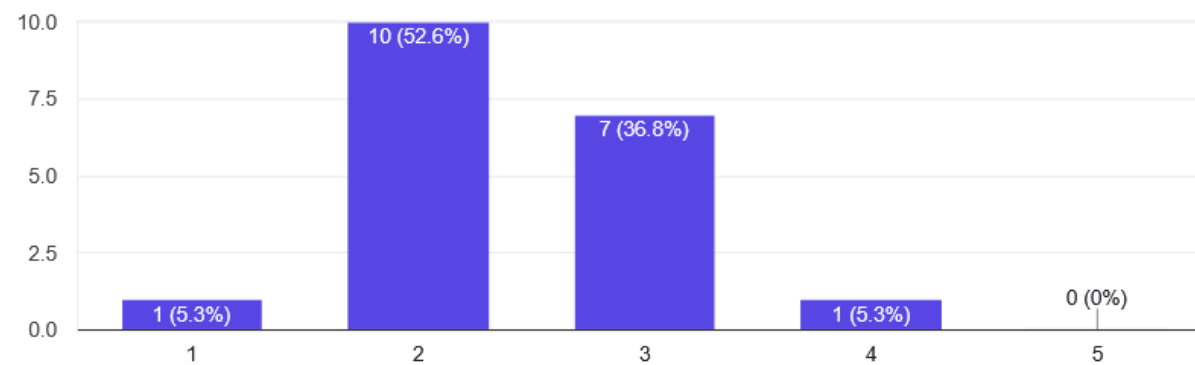


Druk en spanning

druk is de kracht per oppervlakte-eenheid die op een oppervlak werkt, terwijl spanning de kracht is die binnenin een materiaal wordt overgedragen.

19 responses

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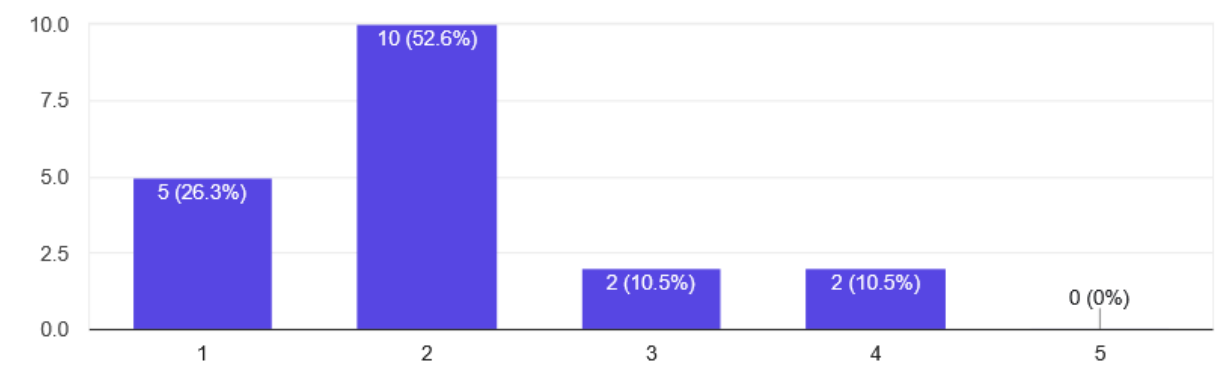


Wrijving

een kracht die de relatieve beweging tussen twee contactoppervlakken tegenwerkt.

19 responses

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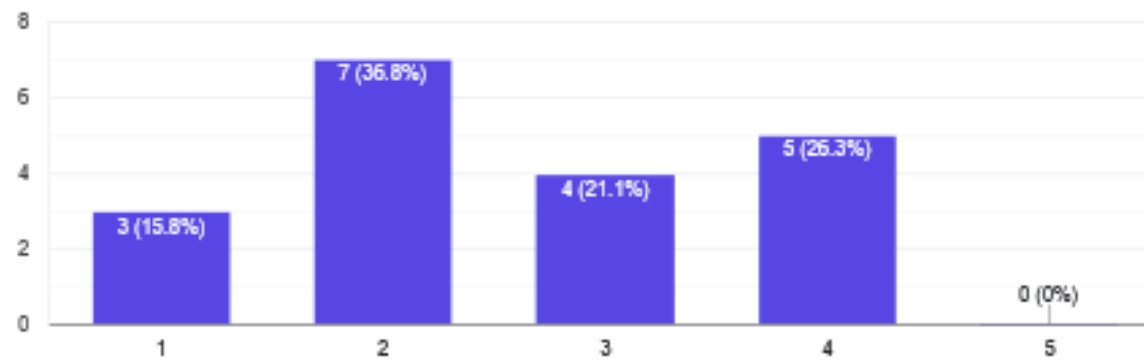


Torsie

torsie is het verdraaien van een object door een moment.

19 responses

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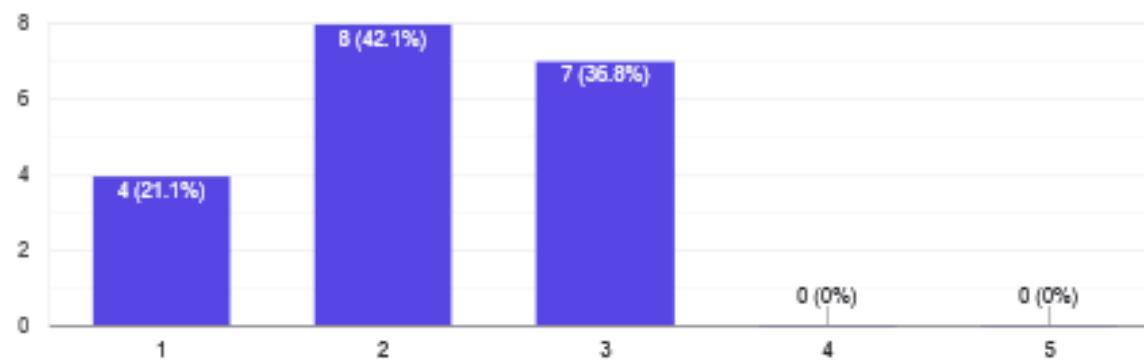


Buiging

buiging is het vervormen van een voorwerp doordat er een kracht of moment loodrecht op de lengte werkt, waardoor het krom trekt.

19 responses

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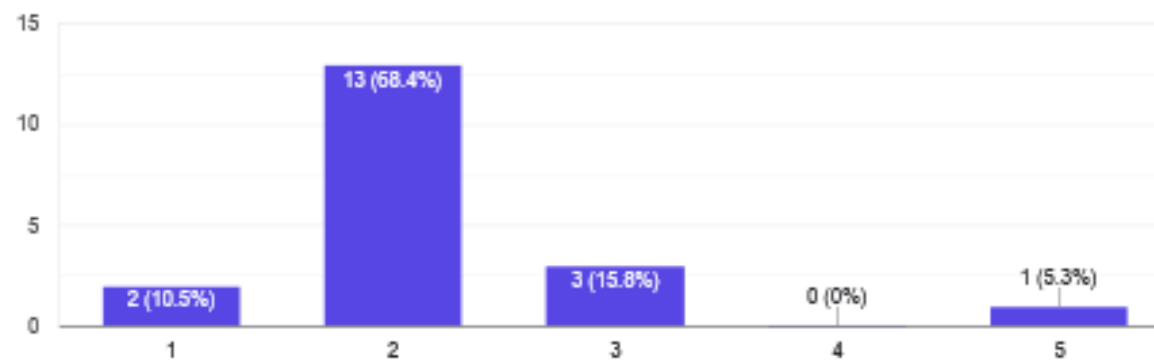


Veerkracht

veerkracht is de kracht waarmee een veer of elastisch materiaal terug wil keren naar zijn oorspronkelijke vorm na vervorming.

19 responses

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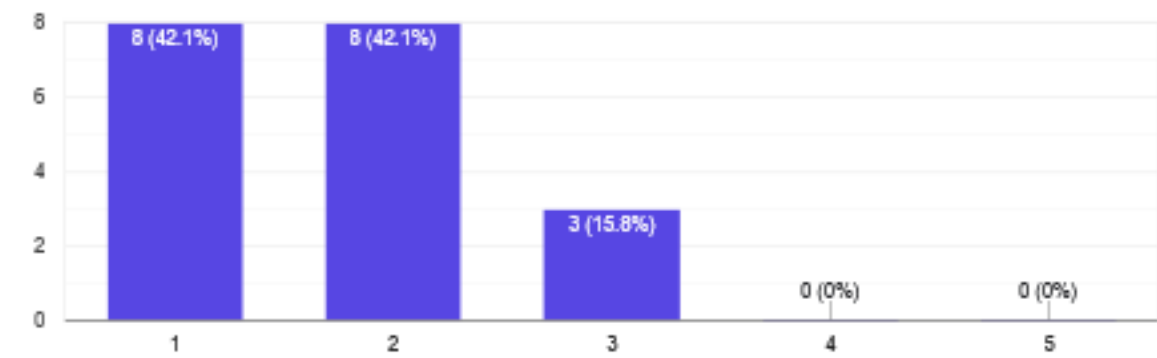


Versnelling

versnelling is de verandering van snelheid per tijdseenheid.

19 responses

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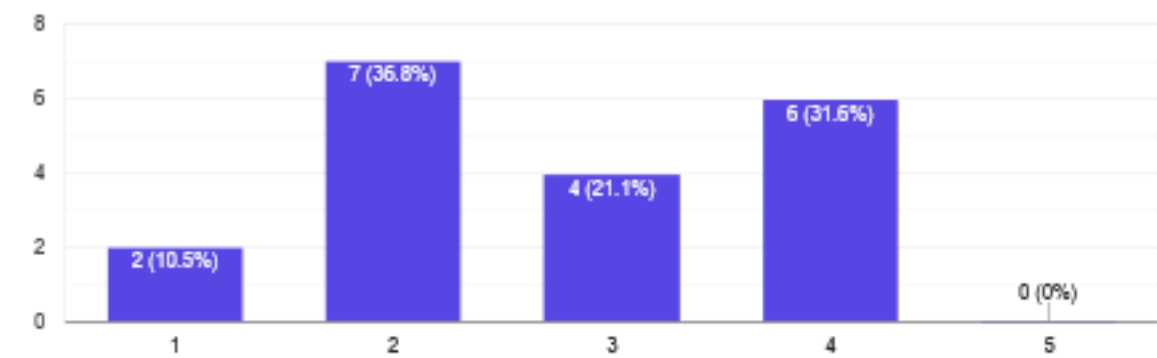


Trillingen/resonantie

trillingen zijn herhaalde bewegingen rond een evenwichtsstand, en resonantie treedt op wanneer een systeem extra sterk gaat trillen bij zijn eigen frequentie.

19 responses

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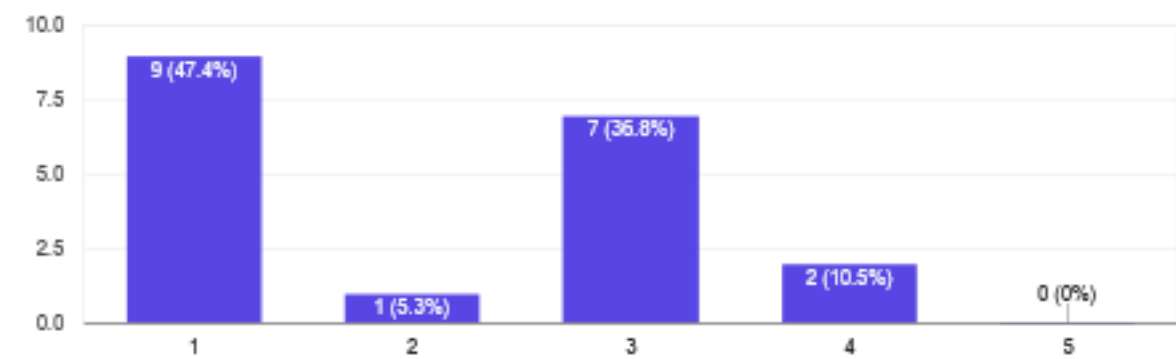


Translatie en Rotatie

translatie is beweging zonder draaien waarbij alle punten even ver verschuiven, en rotatie is beweging waarbij een voorwerp draait rond een as.

19 responses

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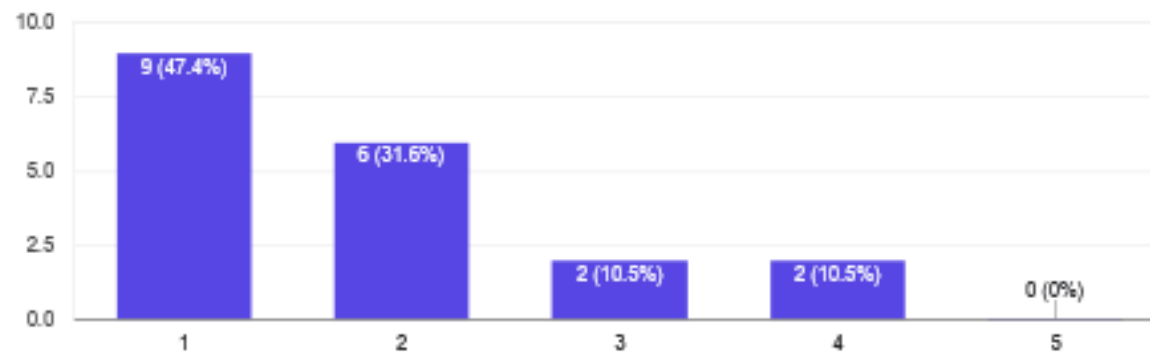


Snelheid/versnelling

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snelheid is hoe snel en in welke richting een voorwerp beweegt, en versnelling is hoe snel die snelheid verandert.

19 responses

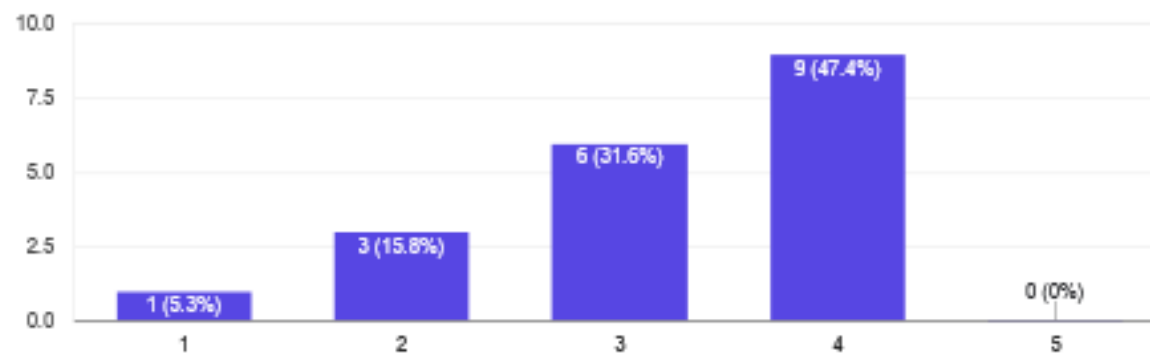


Impuls en momentum

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Momentum geeft aan hoe moeilijk het is om een bewegend voorwerp te stoppen. Impuls beschrijft hoeveel de kracht een beweging verandert in een bepaalde tijd.

19 responses

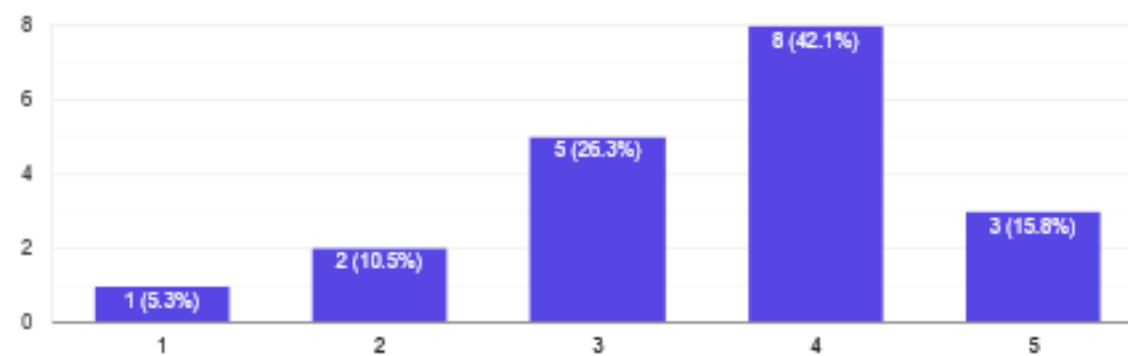


Traagheids moment

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een maat voor hoe moeilijk het is om een voorwerp in rotatie te versnellen of af te remmen rond een bepaalde as.

19 responses

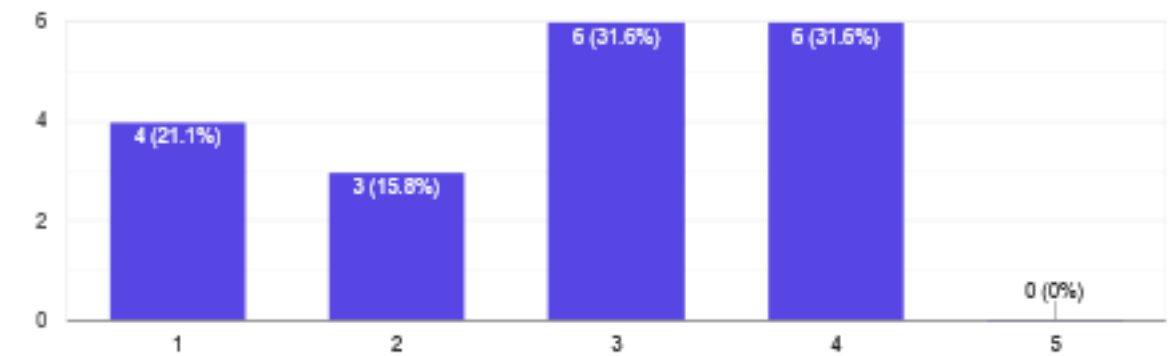


Mechanismen

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systemen van verbonden onderdelen die beweging of kracht overbrengen en omzetten.

19 responses

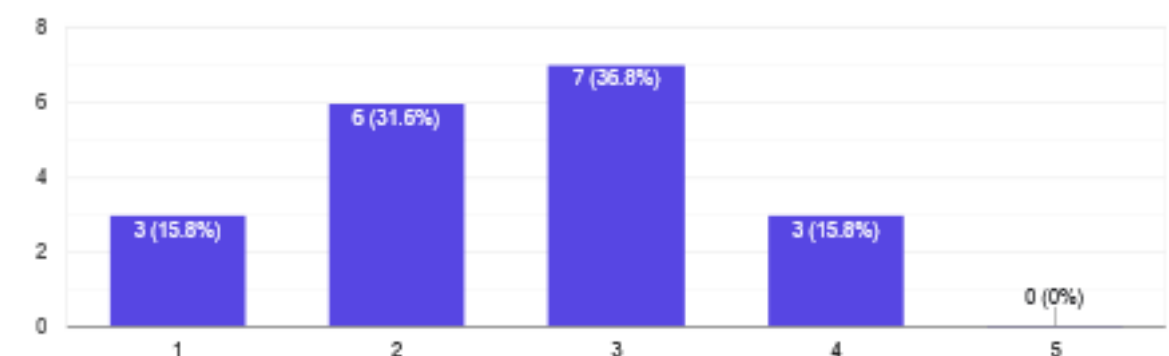


Vakwerken

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constructies van staven die via knooppunten verbonden zijn en krachten vooral als trek en druk doorgeven.

19 responses

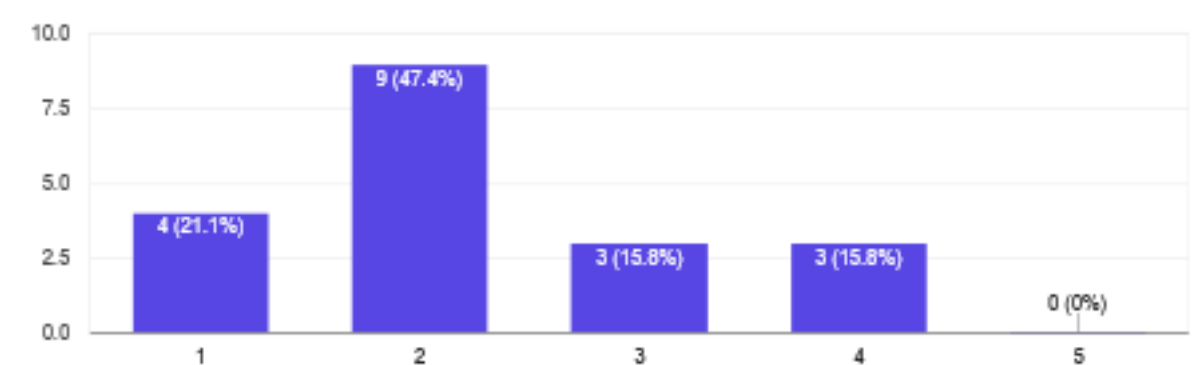


Tandwielen en pulley's

[Copy chart](#)

systemen die beweging en kracht overbrengen en aanpassen door rotatie of via een riem of ketting.

19 responses

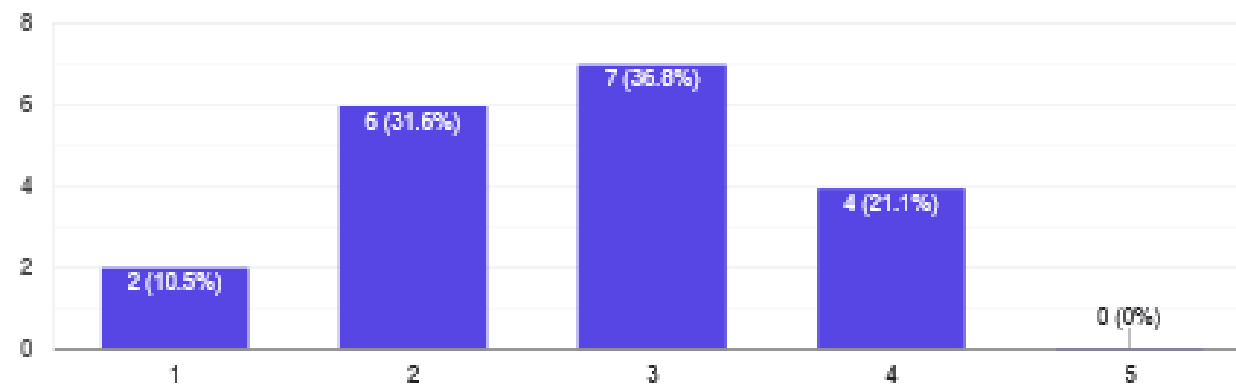


Hoeksnelheid

de snelheid waarmee een voorwerp draait, uitgedrukt als hoekverandering per tijdseenheid.

19 responses

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Appendix C Research template building board size

Research Question Template

Research Entry

Title: What is the best size (in mm) for the board to allow 4 students to interact with the mechanical garden (Learning tool)?

Date: 17/05/26

Project Phase: After the first big testing phase.

1. SCQA (Framing the Question)

Situation:

The mechanical garden should be able to be used by 4 students. These 4 students should have minimal difficulties reaching the mechanical garden build plate. This will allow all students to interact with the mechanical garden.

Complication:

During the first testing phase it became clear that the plate of the mechanical garden was too small to allow for bigger structures to be built. 1 student could easily interact with the board but when presented to a larger group of students it became clear that the board (building surface) should be expanded. This is to prevent students (users) from reaching too much over the table and maybe dislodging some of the [build](#) structures.

Question:

What is the best size (in mm) for the board to allow 4 students to interact with the mechanical garden (Learning tool)?

Answer (Initial Hypothesis - optional):

The first board was based on an estimation and not substantiated by research. The board now is 400mm x 600mm. When looking at 4 player board games my initial thought is that the board needs to be bigger and may be squarer.

2. Research Objective

To be able to create the optimal size building plate for the mechanical garden so it can easily and effectively be used by up to 4 students at the time.

3. Method / Approach

Type of Research:

Literature

☐ Literature review ☐ User research ☐ Experiment ☐ Benchmark ☐ Other: _____

Steps Taken:

1. Looking at Dined to discover the arm length of Dutch students. This can give some idea of how far an average student is able to reach.
2. Looking at academic research to see if there is any source which states the optimal size for a game board.
3. Looking at existing game boards (for games which are played with 4 people) to see if there is a rule of guideline to follow.

4. Findings / Results

<https://bostontec.com/literature/Bostontec-Ergonomic-Reach-Zones.pdf>

- "Reach Zones are areas within an employee's reach (usually centered around a specific workstation) that are frequented to perform daily tasks. On the other hand, Ergonomic Reach Zones are areas that employees can comfortably reach without subjecting their bodies to unnecessary harm."

- "Zone 1 is called the "Neutral Reach Zone," meaning that this is the area that the human body will be most comfortable in for an extended period and will cause the least amount of strain on the body. Items placed in this zone are easy to reach. Here is where we should position the most frequently used items. It's the zone where most of the work motions should happen."

- As we show in Figure 1.1 below, the range of motion in this zone focuses on movements not exceeding the maximum reach of the average forearm with a bent elbow, meaning that the natural range is up to 14" in the horizontal plane and 6" in the vertical plane (as shown in Figure 1.2).



https://www.valin.com/documents/pdf/Bosch-Ergonomic-Guidebook.pdf?utm_source=chatgpt.com

- Optimal reach zone is +/- 400mm in a seated position while using two hands.

<https://dined.io.tudelft.nl/en/database/tool>

- The average arm length of the Dutch student (2016) is 742mm. This is measured from the back of the student to the hand grabbing an object. The average chest depth should be subtracted from this number to find how far a student can reach. Average chest depth is 237mm, so the average distance is 505mm (this is when the arm is fully stretched out).

https://www.fun.com/best-selling-board-games-all-time.html?srltid=AfmBOorIDVbrwTiro_jfFPvylpNp40jR8olLGDQBKAm_VIWoaMXFphCQ

- Looking at the most successful 4 player board games (in terms of sales) to determine the board size.
- Monopoly 508 x 508 mm 258064
- Scrabble 355 x 355 mm 126025
- Cluedo 508 x 508 mm 258064
- Risk 508 x 762 mm 387096

Average overall (When looking at the named board games) Average surface area 257312.25 so 507,26 x 507,26 mm

5. Analysis

Interpretation:

The research presented the project with 3 optimal reach areas. 355mm, 400mm and the average reach of a Dutch student in 2016 is 505mm. Because the mechanical garden building plate should be reachable from both sides of the table it is important that the size of the table is also considered. 507,26 x 507,26 mm was found when looking at existing board games.

Surprises:

The average reach and optimal working area is less than expected.

6. Conclusion (Answer to the Question)

Final answer:

The size of the mechanical garden building board will be 500x500

Supporting reasoning:

Popular board games such as monopoly use a similar size, when looking at the sources of the optimum reach area the 500x500mm area is bigger than recommended. This is because the sources look at 1 user using the area before them. The mechanical garden building board is meant to be used by 4 people at the same time which occurs when the 4 students are sitting face to face. Therefore, alle students need to be able to reach it and therefore the area is bigger,

7. Implications for Project

The building board will be 500x500 mm a little bit smaller than expected because the edges of the board need to be protected by a 3D printed edge. This edge will add some mm to the overall board.

8. Next Steps

Create the 500x500 board by cutting a 0.8mm metal sheet into this size.

9. Limitations

It is difficult to predict all table sizes on which the mechanical garden will be used. Tables may be bigger or smaller. It is also possible that existing tables will be phased out in the upcoming year.

Research Question Template

Research Entry

Title: "How does increasing the number of magnets affect the total magnetic force?"

Date:

Project Phase: Prototyping

1. SCQA (Framing the Question)

Situation:

When using the prototype, it became clear that in some instances the individual parts placed on the building board of the mechanical garden would shift if the forces applied to them by the motor became too high. After increasing the number of magnets in the part, it was observed that the magnetic force did increase but not by how much was expected.

Adding magnets did not linearly increase force.

Complication:

Adding more magnets did not have the expected and wished result.

Question:

Why Is adding more magnets to my building parts not increasing the magnetic force by the amount that I expected.

Answer (Initial Hypothesis - optional):

Multiple magnets in the same part might counteract each other resulting in a somewhat stronger pull but not by as much as expected.

2. Research Objective

3. Method / Approach

Type of Research:

literature

Steps Taken:

Literate research using google scholar.

4. Findings / Results

<https://www.sciencedirect.com/science/article/abs/pii/S0304885313006732>

- With growing availability of high-energy magnets of various types, forms and functionalities, the range of applications employing them is constantly expanding

https://jontallen.ece.illinois.edu/Public/Allen/Noori-pdf/VokounBeleggiaHellerSittner.09.pdf?utm_source=chatgpt.com

- Attraction forces between permanent magnets are established by magnetostatic interactions.
- However, when dealing with permanent magnets utilized as, e.g., magnetic fasteners, modeling near-contact attractive magnetostatic forces requires a more advanced treatment that takes into account shape effects

<https://arxiv.org/pdf/1708.01880>

- Mis orienting magnets can lead them to become less magnetic. "This decrease of the coercive field is caused by misorientation, demagnetizing fields and thermal fluctuations."

<https://www.mdpi.com/2076-0825/7/3/54>

- The placement of permanent magnets is important but difficult to determine experimentally.

5. Analysis

Interpretation:

How magnets are placed ~~in~~ a 2d plane is important because it can influence the magnetic field. Although to determine of the placement is optimal is difficult to determine

6. Conclusion (Answer to the Question)

Final answer:

Adding an extra magnet may not result in a linear increase in strength. The geometry0placement of the magnets is important.

Adding a fourth magnet improved the holding force, but not proportionally. Literature suggests that demagnetizing fields and the geometry of permanent magnet arrays influence the resulting magnetic field and magnetic performance.

7. Implications for Project

Although adding a 4th magnet did not linear increase the magnetic strength it did increase it a little bit. So the 4th magnet is added.

8. Next Steps

Adding the 4th magnet in the system and all parts of the system.

9. Limitations

Adding magnets means higher costs and changing the entire system/ so 4 magnets is now considered to be [the a](#) well enough amount.

```
1 import time
2 import board
3 import digitalio
4 import pwmio
5 import analogio
6 from adafruit_debouncer import Debouncer
7 from adafruit_motor import servo
8
9 # -----
10 # Motor: IN1..IN4 op A2..A5
11 # -----
12 IN1 = digitalio.DigitalInOut(board.A2)
13 IN2 = digitalio.DigitalInOut(board.A3)
14 IN3 = digitalio.DigitalInOut(board.A4)
15 IN4 = digitalio.DigitalInOut(board.A5)
16
17 for p in (IN1, IN2, IN3, IN4):
18     p.direction = digitalio.Direction.OUTPUT
19     p.value = False
20
21 SEQ = [
22     (1, 1, 0, 0),
23     (0, 1, 1, 0),
24     (0, 0, 1, 1),
25     (1, 0, 0, 1),
26 ]
27
28 # Lower STEP_DELAY = faster
29 MIN_STEP_DELAY = 0.001
30 MAX_STEP_DELAY = 0.050
31
32 STEP_DELAY = 0.003
33
34 def set_coils(a, b, c, d):
35     IN1.value = bool(a)
36     IN2.value = bool(b)
37     IN3.value = bool(c)
38     IN4.value = bool(d)
```



```

43 def map_range(value, in_min, in_max, out_min, out_max):
44     return out_min + (value - in_min) * (out_max - out_min) / (in_max - in_min)
45
46 # -----
47 # Buttons naar GND, met interne pull-up
48 # D4 = stepper mode cycle:
49 #     1 normal rotation
50 #     2 oscillating movement
51 #     3 off
52 # D13 = linksom
53 # D2 = rechtsom
54 # -----
55 def make_button(pin):
56     io = digitalio.DigitalInOut(pin)
57     io.direction = digitalio.Direction.INPUT
58     io.pull = digitalio.Pull.UP
59     return Debouncer(io)
60
61 btn_power = make_button(board.D4)
62 btn_left = make_button(board.D13)
63 btn_right = make_button(board.D2)
64
65 # -----
66 # Rotary angle sensor
67 # Signal pin = A0
68 # VCC = 3.3V
69 # GND = GND
70 # -----
71 angle_sensor = analogio.AnalogIn(board.A0)
72
73 # -----
74 # Servo on D7
75 # -----
76 SERVO_PIN = board.D7
77
78 CENTER_ANGLE = 180
79 SWING_DEG = 90
80

```

```

81 LEFT_ANGLE = max(0, CENTER_ANGLE - SWING_DEG // 2)
82 RIGHT_ANGLE = min(180, CENTER_ANGLE + SWING_DEG // 2)
83
84 SERVO_STEP_DEG = 1
85 SERVO_STEP_DELAY = 0.02
86
87 pwm = pwmio.PWMOut(SERVO_PIN, duty_cycle=0, frequency=50)
88 my_servo = servo.Servo(pwm)
89
90 servo_on = True
91 servo_angle = LEFT_ANGLE
92 servo_dir = 1
93 last_servo_move = 0.0
94
95 # -----
96 # Stepper state
97 # motor_mode:
98 # 0 = off
99 # 1 = normal continuous rotation
100 # 2 = oscillating back and forth
101 # -----
102 motor_mode = 0
103 direction = 1
104 seq_index = 0
105
106 OSC_STEPS = 200
107 osc_count = 0
108 osc_dir = 1
109
110 try:
111     while True:
112         # Update buttons
113         btn_power.update()
114         btn_left.update()
115         btn_right.update()
116

```

```

117 # -----
118 # Rotary angle sensor speed control
119 # -----
120 sensor_value = angle_sensor.value
121
122 # sensor_value is 0 to 65535
123 # Turn one way = slow, other way = fast
124 STEP_DELAY = map_range(
125     sensor_value,
126     0,
127     65535,
128     MAX_STEP_DELAY,
129     MIN_STEP_DELAY
130 )
131
132 if STEP_DELAY < MIN_STEP_DELAY:
133     STEP_DELAY = MIN_STEP_DELAY
134
135 if STEP_DELAY > MAX_STEP_DELAY:
136     STEP_DELAY = MAX_STEP_DELAY
137
138 # Stepper mode cycle:
139 # off -> normal -> oscillating -> off
140 if btn_power.fell:
141     motor_mode = (motor_mode + 1) % 3
142
143     if motor_mode == 0:
144         release_stepper()
145
146     elif motor_mode == 1:
147         direction = 1
148
149     elif motor_mode == 2:
150         osc_count = 0
151         osc_dir = direction
152
153 # Stepper direction buttons
154 if btn_left.fell:

```

```

155     direction = 1
156     if motor_mode == 2:
157         osc_dir = 1
158
159 if btn_right.fell:
160     direction = -1
161     if motor_mode == 2:
162         osc_dir = -1
163
164 # Stepper run
165 if motor_mode != 0:
166     set_coils(*SEQ[seq_index])
167
168     if motor_mode == 1:
169         step_dir = direction
170
171     elif motor_mode == 2:
172         step_dir = osc_dir
173         osc_count += 1
174
175         if osc_count >= OSC_STEPS:
176             osc_count = 0
177             osc_dir *= -1
178
179     seq_index = (seq_index + step_dir) % len(SEQ)
180
181     time.sleep(STEP_DELAY)
182
183 else:
184     time.sleep(0.001)
185
186 # Servo run
187 if servo_on:
188     now = time.monotonic()
189
190     if now - last_servo_move >= SERVO_STEP_DELAY:
191         last_servo_move = now
192

```


Appendix F Excercise booklet

```
192     servo_angle += SERVO_STEP_DEG * servo_dir
193
194
195     if servo_angle >= RIGHT_ANGLE:
196         servo_angle = RIGHT_ANGLE
197         servo_dir = -1
198
199     elif servo_angle <= LEFT_ANGLE:
200         servo_angle = LEFT_ANGLE
201         servo_dir = 1
202
203     my_servo.angle = servo_angle
204
205 finally:
206     release_stepper()
207     pwm.duty_cycle = 0
208
```

Windshield wipers.

Hello engineer!

So, you are in the process of designing and constructing your own robot. Robots are diverse machines that are often created for a specific purpose or task. These tasks can range from very simple actions, such as driving forward and backward, to far more advanced challenges like picking up certain objects, lifting heavy materials, sorting items, or even helping people in everyday life.

Engineers design robots to solve problems, make tasks easier, and work in places where humans may struggle or where extra precision is needed. Some robots are built for factories, others for exploring space or the deep ocean, and some are even designed to assist in hospitals and homes.

One important movement many robots need to perform is gripping or picking up objects. Because the gripping action is so important and complicated, you will be tasked with designing and constructing a gripper while following these exercises.

Everybody knows the familiar movement of a windshield wiper, so this will be a simple exercise to get started.

Please design and construct a windshield wiper mechanism using the continuously rotating mode on the control panel. It does not matter how large the wiping area is, as long as the mechanism is able to create the wiping motion. (Draw your design in the box below).

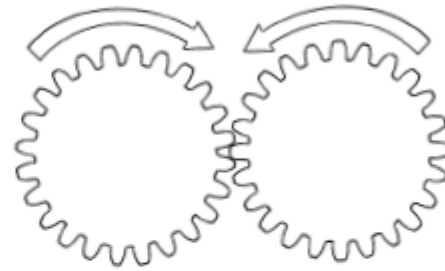
For this task, you will have approximately 10 minutes.



Making the mechanism move in the right direction

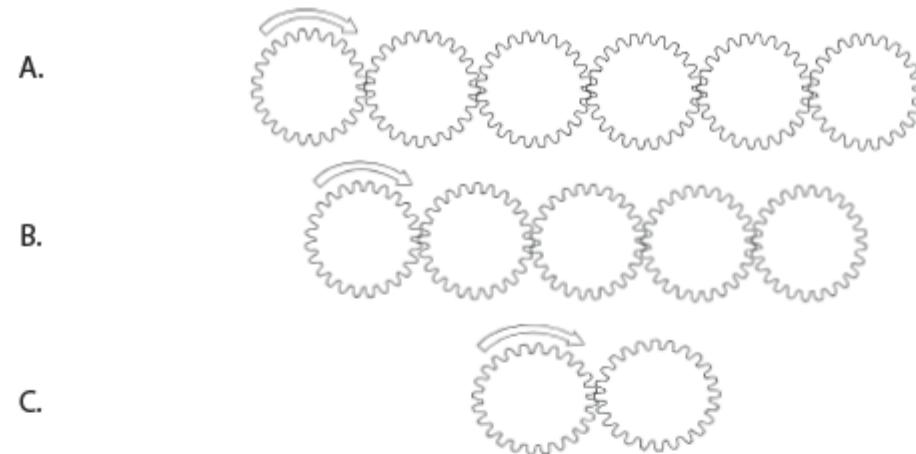
When two gears **mesh**, they rotate in opposite directions. Therefore, the rotational direction of a gear depends on the number of gears in the system, each additional gear reverses the direction (of the last gear in the system) again.

Mesh (in gears):
The engagement of gear teeth where two gears interlock.



Prototyping

Construct the following gear systems. For each system, write down on this sheet, or discuss with a neighbour, which direction you think the last gear will rotate. After that, test your prediction.



A.

B.

C.

What design rules can you construct for yourself to remember how the rotational direction of a gear in a system is influenced?
Write them down below.

Creating the right speed or torque for the job

Gear ratios describe how motion and force are transferred between gears. By changing the size and number of teeth of gears, you can control how fast something moves or how much force it produces. This is essential in many mechanical systems, from simple machines to complex robots.

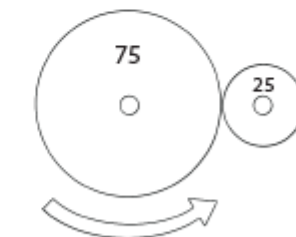
In this exercise, you will explore how gear ratios work by building and analyzing different gear systems. You will learn how to calculate gear ratios and understand their effect on speed and torque.

A gear ratio is written as, for example, 1:3. This means that for every 1 rotation of the driving (input) gear, the driven (output) gear rotates 3 times. Gear ratios determine how speed and force (torque) are transferred in a system:

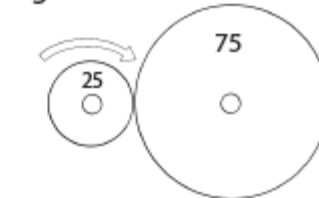
Formula

$$\text{Gear Ratio} = \frac{T_{\text{driven}}}{T_{\text{driver}}}$$

Low



High



low gear ratio (e.g. 1:3) *increases speed but reduces torque*. The output gear spins faster than the input, but with less force.

high gear ratio (e.g. 3:1) *increases torque but reduces speed*. The output gear turns more slowly, but with greater force.

Understanding the difference between high and low gear ratios is important when designing mechanisms. For example, a gripper may need a high gear ratio to generate enough force (torque), while a wheel system may use a low gear ratio for higher speed.

Prototyping

Please construct the following gear ratios using the number of gears specified in each exercise. Write down below if it is a low or high gear ratio. Remember the motor gear has 40 teeth and is included.

A.	Ratio- 1:2 Amount of gears- 2	B.	Ratio- 2:1 Amount of gears- 4

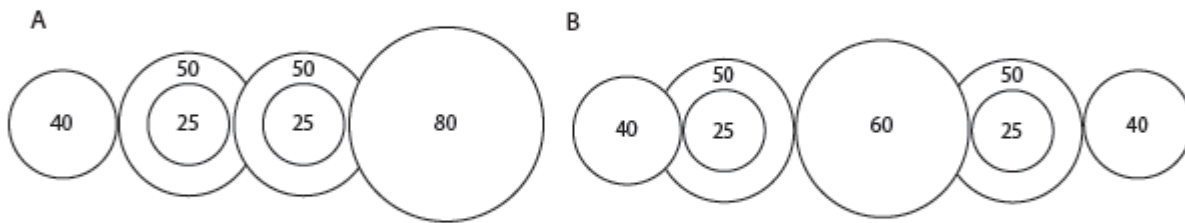
Systems of gears can be combined, when doing this the ratios of the separate systems have to be combined by multiplying them.

Build two different systems for gears each with a different gear ratio, activate them individually and observe the movement. Now combine them and observe again.

Please use the following space to a 2D draw representation of the gear systems and their ratios, also write down the combined ratio of the two systems.

More speed or torque in a smaller space

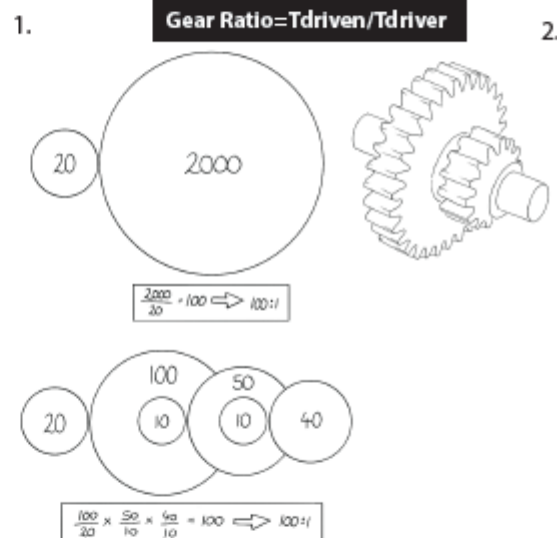
Compound gears are systems where two or more gears are fixed on the same shaft and rotate together. By combining gear sets, compound gear systems can significantly increase torque or reduce/increase speed, making them useful in many mechanical applications such as gearboxes. Please construct the following mechanisms in the mechanical garden and try them. After try inverting the compound gears and observe what happens. (Remember the gear on the motor has 40 teeth).



When a compound gear is driven, all gears mounted on the same shaft rotate at the same speed. For example, if a compound gear consists of a lower gear with 50 teeth and an upper gear with 25 teeth, one full rotation of the shaft will cause both gears to complete exactly one full rotation (2).

When combined with other compound gears it is possible to further reduce or increase the speed and up the torque. This is especially helpful when constructing mechanisms which need a lot of torque or speed.

Compound gears are also really helpful because of their size, you need a much smaller compound gear to be able to get some high ratios. For instance the ratio 100:1 (1).



Prototyping

Please construct the following gear ratios. For each ratio you need to construct a gear train with compound gears. Please make a 2D sketch of your constructed gear train and specify if it is a high or low ratio in the empty box. Remember the motor gear has 40 teeth and should be included.

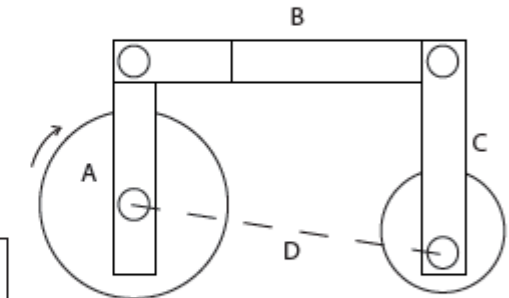
	High or low	Sketch
A. Ratio 8:1		
B. Ratio 1:4		

Creating linear motion from rotation

A planar (in a single plane) four-bar linkage consists of four rigid links: the input link, coupler link, output link, and a fixed link. These links are connected by pin joints.

A four-bar linkage is used to convert rotational motion into linear motion, or the other way around.

Let's start constructing some four-bar linkages. Try to build the following four-bar linkage in the Mechanical Garden using the provided pieces. Turn on the stepper motor and observe the movement of your creation. What happens when you shorten or lengthen links A, B, C, and D? Experiment with different link lengths and write down at least one observation in the box below.



Grashof's law

Before we can start constructing some four-bar linkages of our own you first need the theoretical understanding of Grashof's law. This law makes it possible to calculate the behavior of a four-bar linkage, if it is able to do a full rotation of an oscillating rotation. This can be calculated by the following formula:

$$s + l \leq p + q$$

s is the shortest link
 l is the longest link
 p and q are the remaining two links

If the condition is satisfied, at least one link in the mechanism is able to rotate fully. If the condition is not satisfied, none of the links can complete a full rotation and all motion will be oscillating. Depending on which link is fixed, different types of motion can occur:

How s is connected to the fixed link (ground) defines what kind of mechanism it is.

Crank-crank:

both links can rotate fully

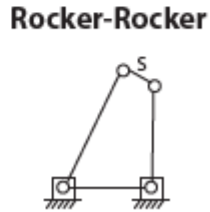
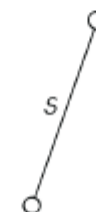
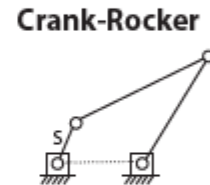
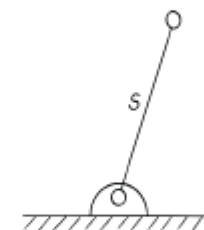
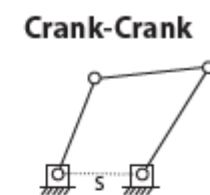
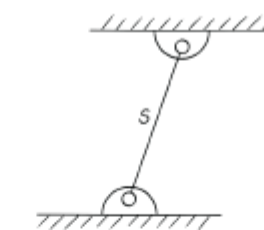
Crank-rocker:

one link rotates full, the other oscillates

Rocker-rocker:

both links only oscillate

By applying Grashof's law, you can determine in advance how your mechanism will behave before building it.



Creating linear motion from rotation

Most of the time we use a four-bar linkage to construct mechanisms to convert rotational movement into linear movement (**Crank-Rocker**). Please try to construct 2 different four-bar mechanisms. 1- where the movement of the rocker is small. 2- where the movement of the rocker is big. Please quickly sketch the design in the boxes below and think of a possible use case.

1. Small linear movement

2. Big linear movement

Prototyping

As a designer, you are tasked with developing a mechanism to wipe clean the window of an observatory during rainstorms. The observatory window must remain as clear as possible so observations can continue even in poor weather conditions. To achieve this, you need to design a mechanism that can create a controlled wiping motion across the surface of the window.

Only one rotational motor is provided, so your design must convert continuous rotary motion into the desired oscillating motion of the wiper. Please sketch your 2D design in the box below.

Design exercise

You have constructed, gear trains, gear trains including compound gears, calculated gear ratios and dabbled in the art of constructing planar four-bar linkages.

Now it is time to show your skills as a designer and combine these gold nuggets of knowledge in the crucible of your mind.

Challenge

Researchers have discovered a new strange solid substance, while excavating the earth soil. After some analysing (from a distance) it has been found that the solid substance has a high density similar to the density of tungsten (19.3 g/cm^3) and is highly toxic for humans to touch. You are therefore chosen to design and construct a gripper mechanism which is able to produce a high grip force to extract this dangerous material.

Write down a list of requirements, make a 2D sketch and start prototyping. At the end please make a picture of your design and share with your peers and teacher.

Appendix G Scriptsolid code gear designer

```
// Parametric Spur Gear with engraved tooth number,  
// readable number on both sides, 2 magnet holes,  
// and slots on both sides only for gears with 25 teeth or more
```

```
/* [User Parameters] */  
teeth = 25;          // [10:1:100]  
module_size = 1.5;   // [0.5:0.1:5]
```

```
/* [Hidden] */  
gear_thickness = 5;  
bore_diameter = 5.2;
```

```
pressure_angle = 20;  
clearance_factor = 0.25;
```

```
flank_steps = 10;  
tip_steps = 6;  
root_steps = 6;  
$fn = 120;
```

```
PI = 3.141592653589793;
```

```
function rad(a) = a * PI / 180;  
function deg(a) = a * 180 / PI;  
function involute_deg(a_deg) = deg(tan(a_deg) - rad(a_deg));  
function polar(r, a_deg) = [r * cos(a_deg), r * sin(a_deg)];  
function clamp(x, lo, hi) = min(max(x, lo), hi);  
function alpha_r_deg(r, rb) = (r <= rb) ? 0 : acos(clamp(rb / r, -1, 1));
```

```
function half_tooth_angle_deg(r, rb, pa_deg, teeth) =  
    90 / teeth + involute_deg(pa_deg) - involute_deg(alpha_r_deg(r, rb));
```

```
function arc_points(r, a1, a2, steps) =  
    [ for (i = [0:steps]) polar(r, a1 + (a2 - a1) * i / steps) ];
```

```
function flank_points(r1, r2, steps, side, rb, pa_deg, teeth) =  
    [ for (i = [0:steps])  
        let(  
            r = r1 + (r2 - r1) * i / steps,  
            a = side * half_tooth_angle_deg(r, rb, pa_deg, teeth)  
        )  
        polar(r, a)  
    ];
```

```
function reverse(v) = [ for (i = [len(v)-1 : -1 : 0]) v[i] ];
```

```
function angle_diff(a, b) =  
    abs(((a - b + 180) % 360) - 180);
```

```
pitch_diameter = module_size * teeth;  
pitch_radius = pitch_diameter / 2;
```

```
addendum = module_size;  
dedendum = module_size * (1 + clearance_factor);
```

```
outer_radius = pitch_radius + addendum;  
root_radius = max(0.2, pitch_radius - dedendum);
```

```
base_radius = pitch_radius * cos(pressure_angle);  
start_radius = max(root_radius, base_radius);
```

```
root_half_angle = half_tooth_angle_deg(base_radius, base_radius, pressure_angle,  
teeth);  
tip_half_angle = half_tooth_angle_deg(outer_radius, base_radius, pressure_angle,  
teeth);
```

```
// =====  
// MAGNET HOLES  
// =====  
magnet_diameter = 6.10;  
magnet_depth = 3.50;
```

```
// Center of each magnet hole is exactly 8.5 mm from gear center  
magnet_radius = 8.5;
```

```
// 2 diagonal holes  
magnet_angles = [135, 315];
```

```
module magnet_holes() {  
    for (a = magnet_angles) {  
        rotate(a)  
        translate([magnet_radius, 0, gear_thickness - magnet_depth])  
        cylinder(  
            h = magnet_depth + 0.15,  
            d = magnet_diameter,
```

```

        $fn = 80
    );
}
}

// =====
// DIAGONAL ENGRAVED NUMBER
// =====
engrave_depth = min(0.6, gear_thickness * 0.25);

// Only the number is engraved
text_string = str(teeth);

text_angle = 45;

// Bigger because the word "teeth" is removed
text_size = clamp(root_radius * 0.24, 2.0, 8.0);

text_radius = root_radius * 0.58;

// Top side readable from above
module top_engraved_text() {
    rotate(text_angle)
    translate([text_radius, 0, gear_thickness - engrave_depth])
    linear_extrude(height = engrave_depth + 0.15)
    text(
        text_string,
        size = text_size,
        halign = "center",
        valign = "center",
        font = "Liberation Sans:style=Bold"
    );
}

// Bottom side readable when gear is flipped over
module bottom_engraved_text() {
    translate([0, 0, -0.15])
    rotate(text_angle)
    translate([text_radius, 0, 0])
    mirror([1, 0, 0])
    linear_extrude(height = engrave_depth + 0.15)
    text(
        text_string,
        size = text_size,
        halign = "center",

```

```

        valign = "center",
        font = "Liberation Sans:style=Bold"
    );
}

// =====
// SPACED RECESSED SLOTS
// Only active from 25 teeth and higher
// =====
slot_depth = min(1.00, gear_thickness * 0.20);

slots_enabled = teeth >= 25;

slot_inner_radius = magnet_radius + magnet_diameter / 2 + 1.2;
slot_outer_radius = root_radius - 1.2;

slot_length = max(0, slot_outer_radius - slot_inner_radius);
slot_center_radius = (slot_inner_radius + slot_outer_radius) / 2;

slot_angle_step = 20;
slot_width = clamp(root_radius * 0.05, 0.7, 2.0);

text_clear_angle = 35;

module rounded_slot_2d(length, width) {
    hull() {
        translate([-length / 2, 0])
        circle(r = width / 2, $fn = 40);
        translate([ length / 2, 0])
        circle(r = width / 2, $fn = 40);
    }
}

module top_spoke_recesses() {
    if (slots_enabled && slot_length > 1.5) {
        for (a = [0 : slot_angle_step : 359]) {
            if (angle_diff(a, text_angle) > text_clear_angle) {
                rotate(a)
                translate([slot_center_radius, 0, gear_thickness - slot_depth])
                linear_extrude(height = slot_depth + 0.15)
                rounded_slot_2d(slot_length, slot_width);
            }
        }
    }
}

```



```

module bottom_spoke_recesses() {
  if (slots_enabled && slot_length > 1.5) {
    for (a = [0 : slot_angle_step : 359]) {
      if (angle_diff(a, text_angle) > text_clear_angle) {
        rotate(a)
        translate([slot_center_radius, 0, -0.15])
        linear_extrude(height = slot_depth + 0.15)
        rounded_slot_2d(slot_length, slot_width);
      }
    }
  }
}

// =====
// SINGLE TOOTH PROFILE
// =====
module tooth_2d() {
  right_root_pt = polar(root_radius, root_half_angle);
  left_root_pt = polar(root_radius, -root_half_angle);

  right_flank = flank_points(start_radius, outer_radius, flank_steps, 1,
    base_radius, pressure_angle, teeth);

  left_flank = flank_points(start_radius, outer_radius, flank_steps, -1,
    base_radius, pressure_angle, teeth);

  tip_arc = arc_points(outer_radius, tip_half_angle, -tip_half_angle, tip_steps);
  root_arc = arc_points(root_radius, -root_half_angle, root_half_angle, root_steps);

  tooth_pts = concat(
    [right_root_pt],
    right_flank,
    tip_arc,
    reverse(left_flank),
    root_arc
  );

  polygon(tooth_pts);
}

module body_2d() {
  circle(r = root_radius);
}

```

```

module gear_2d() {
  union() {
    body_2d();

    for (i = [0 : teeth - 1]) {
      rotate(i * 360 / teeth)
      tooth_2d();
    }
  }
}

// =====
// FINAL GEAR
// =====
module spur_gear() {
  difference() {
    linear_extrude(height = gear_thickness)
    gear_2d();

    // Center bore
    translate([0, 0, -1])
    cylinder(h = gear_thickness + 2, d = bore_diameter);

    // Top-side slots
    top_spoke_recesses();

    // Bottom-side slots
    bottom_spoke_recesses();

    // Magnet holes from top side
    magnet_holes();

    // Top-side engraved number
    top_engraved_text();

    // Bottom-side engraved number, readable when flipped
    bottom_engraved_text();
  }
}

spur_gear();

```

Appendix H Perceived usefulness questionnaire

Mechanical Garden perceived usefulness

Thank you so much for testing the Mechanical garden. I would really like to ask you to fill in this survey, it will take less than 1 minute. Thank you in advance

* Indicates required question

1. Please Write your name *

2. The Mechanical Garden helped me better understand the mechanical principles covered during the exercises. *

Mark only one oval.

1 2 3 4 5 6

Stro ☐ ☐ ☐ ☐ ☐ ☐ Strongly agree

3. Interacting with the Mechanical Garden made it easier to understand mechanical movement than learning through theory alone. *

Mark only one oval.

1 2 3 4 5 6

Stro ☐ ☐ ☐ ☐ ☐ ☐ Strongly agree

4. The Mechanical Garden encouraged me to actively experiment with different mechanical solutions. *

Mark only one oval.

1 2 3 4 5 6

Stro ☐ ☐ ☐ ☐ ☐ ☐ Strongly agree

5. After using the Mechanical Garden, I feel more confident in applying mechanical principles during a design project. *

Mark only one oval.

1 2 3 4 5 6

Stro ☐ ☐ ☐ ☐ ☐ ☐ Strongly agree

6. I believe the Mechanical Garden would be a valuable addition to engineering courses and or projects, for example the IDE bachelor course DP3. *

Mark only one oval.

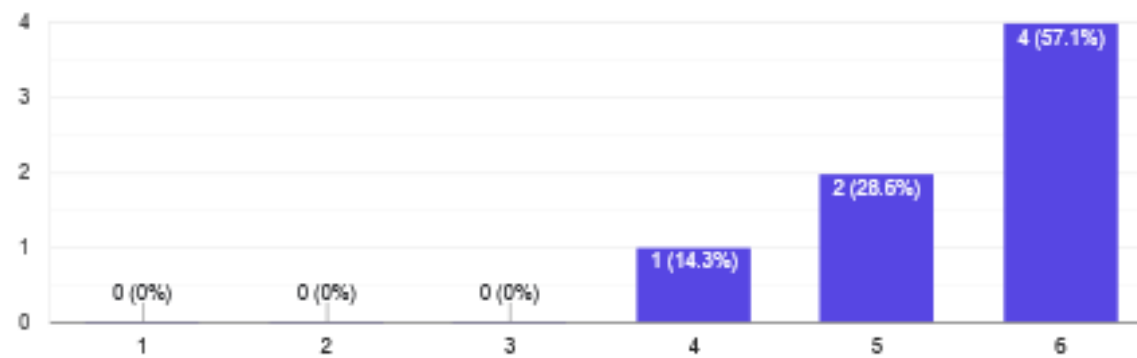
1 2 3 4 5 6

Stro ☐ ☐ ☐ ☐ ☐ ☐ Strongly agree

The Mechanical Garden helped me better understand the mechanical principles covered during the exercises.

[Copy chart](#)

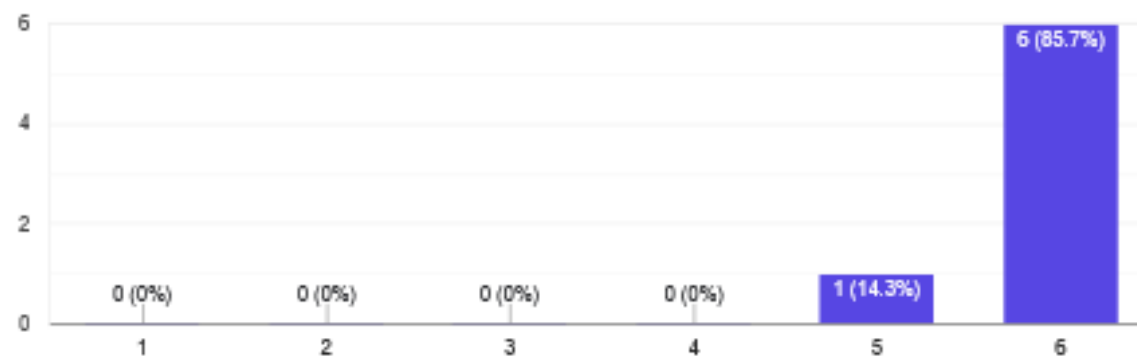
7 responses



Interacting with the Mechanical Garden made it easier to understand mechanical movement than learning through theory alone.

[Copy chart](#)

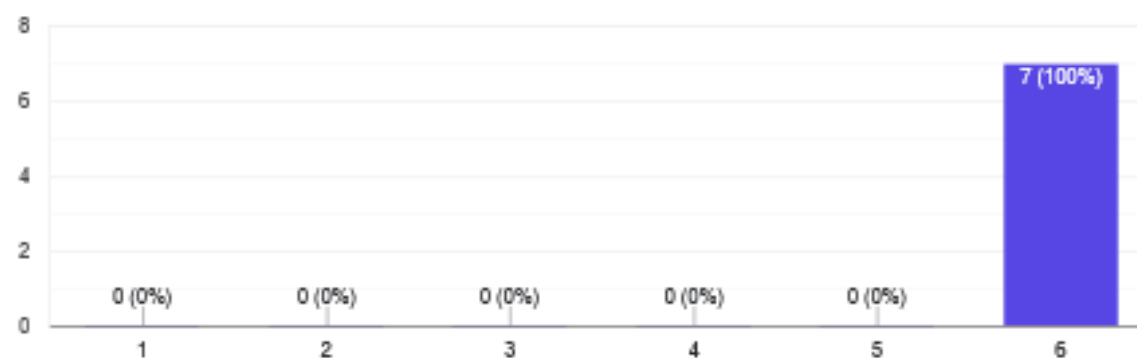
7 responses



The Mechanical Garden encouraged me to actively experiment with different mechanical solutions.

[Copy chart](#)

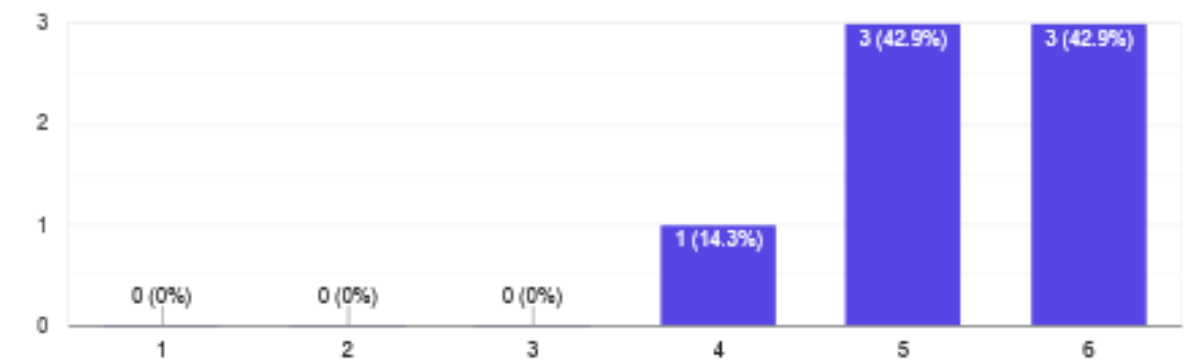
7 responses



After using the Mechanical Garden, I feel more confident in applying mechanical principles during a design project.

[Copy chart](#)

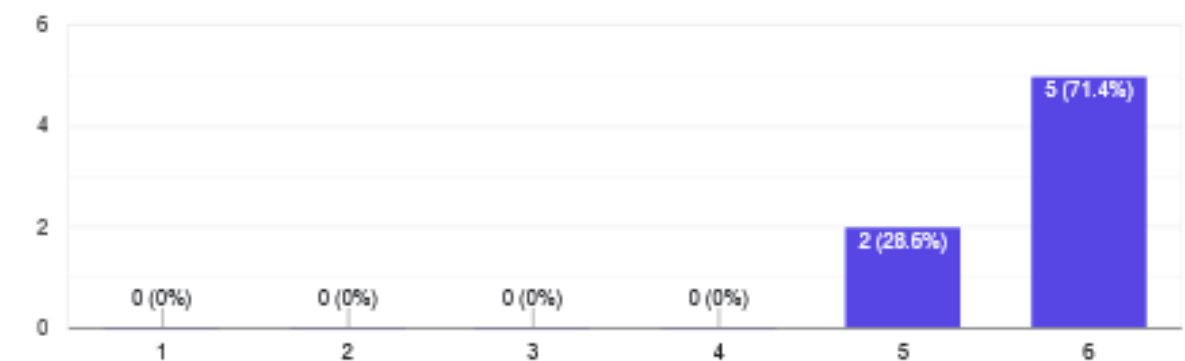
7 responses



I believe the Mechanical Garden would be a valuable addition to engineering courses and or projects, for example the IDE bachelor course DP3.

[Copy chart](#)

7 responses



Appendix I Bill of materials

Part (3D printed)	Material	Amount of magnets (Per part)	Amount to print (Components)	Cost in € (Production and Material cost combined based on 22,99 euro spool)	Amount of material (g)	Fillament color (Bambu labs)
Building plate border (Corner)	Bambu Lab PLA Matte	0	4	€ 2,60	113,29	Bone white (11103)
Building plate border (Side)	Bambu Lab PLA Matte	0	8	€ 3,46	150,41	Bone white (11103)
Motor mount	Bambu Lab PLA Matte	7	1	€ 0,40	17,52	Latte brown (11800)
Motor Gear	Bambu Lab PLA Matte	2	1	€ 0,11	4,43	Apple green (11502)
Magnetic parametric gear (25 teeth)	Bambu Lab PLA Matte	2	2	€ 0,21	8,96	Apple green (11502)
Magnetic parametric gear (30 teeth)	Bambu Lab PLA Matte	2	2	€ 0,30	12,95	Apple green (11502)
Magnetic parametric gear (35 teeth)	Bambu Lab PLA Matte	2	2	€ 0,39	17,16	Apple green (11502)
Magnetic parametric gear (40 teeth)	Bambu Lab PLA Matte	2	2	€ 0,51	22	Apple green (11502)
Magnetic parametric gear (50 teeth)	Bambu Lab PLA Matte	2	2	€ 0,76	33,01	Apple green (11502)
Magnetic parametric gear (60 teeth)	Bambu Lab PLA Matte	2	2	€ 1,06	46,18	Apple green (11502)
Gear mounting base (Small)	Bambu Lab PLA Matte	4	8	€ 1,38	60,11	Latte brown (11800)
Gear mounting base (Big)	Bambu Lab PLA Matte	5	2	€ 0,83	36,04	Latte brown (11800)
Magnetic building disc	Bambu Lab PLA Matte	4	8	€ 0,50	21,88	Latte brown (11800)
Magnetic four_bar linkage (With fence)	Bambu Lab PLA Matte	7	4	€ 0,42	18,2	Latte brown (11800)
Magnetic four_bar linkage (Without fence)	Bambu Lab PLA Matte	7	4	€ 0,38	16,64	Latte brown (11800)
Magnetic four_bar linkage (On gear)	Bambu Lab PLA Matte	6	2	€ 0,21	9,21	Latte brown (11800)
Magnetic four_bar linkage (Gear)	Bambu Lab PLA Matte	3	2	€ 0,70	30,34	Apple green (11502)
Magnetic four-bar linkage Holder (Normal)	Bambu Lab PLA Matte	6	5	€ 2,07	89,99	Latte brown (11800)
Magnetic four-bar linkage Holder (Big)	Bambu Lab PLA Matte	6	2	€ 1,22	52,98	Latte brown (11800)
Electronic component holder	Bambu Lab PLA Matte	0	1	€ 0,53	23,16	Bone white (11103)
Magnetic Rack and pinion	Bambu Lab PLA Matte	4	5	€ 0,44	19,01	Apple green (11502)
Rack channel	Bambu Lab PLA Matte	0	4	€ 0,29	12,81	Latte brown (11800)
Part (Other)						
Building plate	0.8 mm sheet metal	0	1	€ 4,66		
28YBJ-48 DC 5V Stepper Motor with ULN2003 Driver	Electronic component	0	1	€ 3,95		
Neodimium magnets	Neodimium	73	0	€ 7,29		
Post-processing						
Powder coating (Per 100 building plates)		0	1	€ 13,63		
Whiteboard Foil (Roll costs € 19,95 25 plates)		0	1	€ 0,80		