

المملكة العربية السعودية

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المملكة العربية السعودية
KINGDOM OF SAUDI ARABIAوزارة التعليم
Ministry of Education

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Deposit number: **1446/19518**ISBN: **978-603-514-068-3**

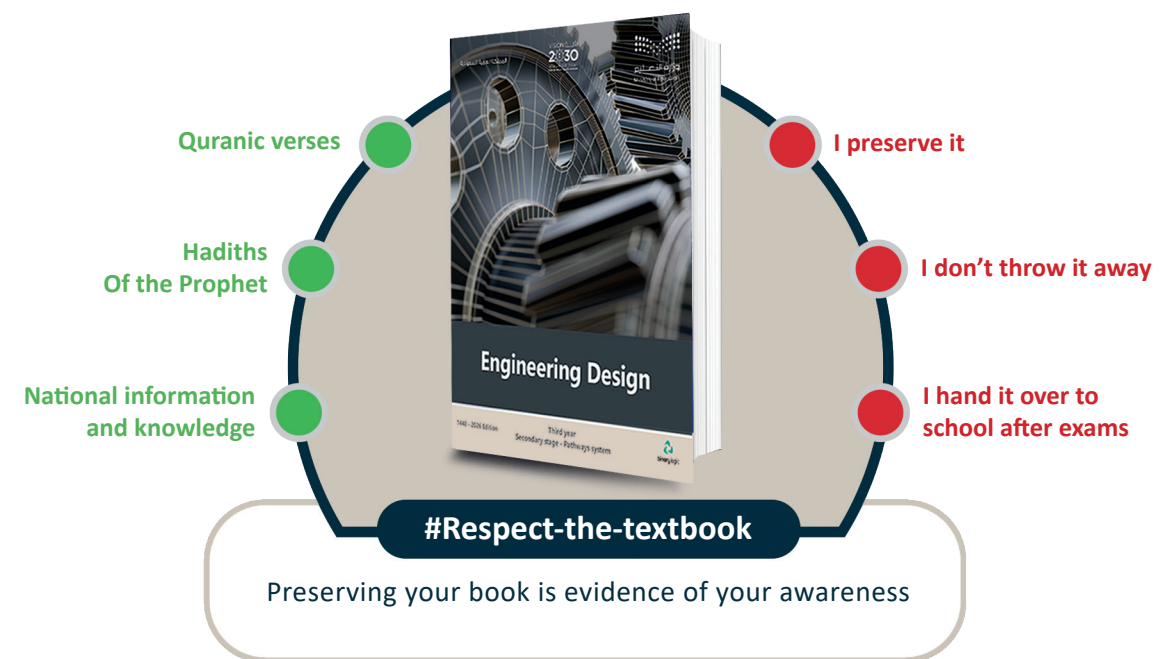
Engineering Design

1448 - 2026 Edition

Third year
Secondary stage - Pathways systemوزارة التعليم
Ministry of Education
2026 - 1448

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قررت وزارة التعليم تدريس
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المملكة العربية السعودية

Engineering Design

Secondary stage - Pathways system

Third year



وزارة التعليم
Ministry of Education
2026 - 1448

The book is distributed freely and cannot be sold.

1448 - 2026 Edition

Publisher: Tatweer Company for Educational Services

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Engineering Design. / National Curriculum Center .-
Riyadh, 2025

224p.; 210*25.5cm

L.D. no. 1446/19518

ISBN: 978-603-514-068-3

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Introduction:

The progress and development of countries is measured by the ability to invest in education, and the extent to which their educational system responds to the requirements and changes of the generations. In the interest of the Ministry of Education sustaining the development of its educational systems, and in response to the vision of the Kingdom of Saudi Arabia 2030, the Ministry of education has taken the initiative to adopt the “Secondary Education Pathways” system to bring about an effective and comprehensive change in high school.

The secondary education pathways system provides a distinguished and modern educational model for high school in the Kingdom of Saudi Arabia, which efficiently contributes to:

- Strengthening the values of belonging to our homeland “the Kingdom of Saudi Arabia” and loyalty to its wise leadership “may God protect him” based on a pure belief supported by the tolerant teachings of Islam.
- Strengthening the values of citizenship by focusing on them in school subjects and activities, in line with the demands of sustainable development, and the development plans in the Kingdom of Saudi Arabia that emphasize the consolidation of both values and identity, based on the teachings of Islam and its moderation.
- Qualifying students in line with future specializations in universities or the required jobs; ensuring the consistency of education outputs with the labor market requirements.
- Enabling students to pursue education in their preferred path at early stages, according to their interests and abilities.
- Enabling students to join specific scientific and administrative disciplines related to the labor market and future jobs.
- Participation of students in an enjoyable and encouraging learning environment in school based on a constructive philosophy and applied practices within an active learning environment.
- Delivering students through an integrated educational journey from the primary level to the end of the high school level and facilitating their transition process to post-general education.
- Providing students with technical and personal skills that help them deal with life and respond to the requirements of their level.
- Expanding opportunities for graduate students through various options in addition to universities, such as: obtaining professional certificates, joining applied faculties, and earning job diplomas.

The pathways system consists of nine semesters that are taught over three years, including a common first year in which students receive lessons in various scientific and humanities fields, followed by two specialized years, in which students study a general path and four specialized paths consistent with their interests and abilities, which are: the Rightful path, Business Administration path, Computer Science and Engineering path, Health and Life path, which makes this system the best for students in terms of:

- The existence of new study subjects that match the requirements of the Fourth Industrial Revolution and development plans, and the Kingdom’s Vision 2030, which aims to develop higher-order thinking, problem-solving, and research skills.
- Elective field programs that are consistent with the needs of the labor market and students’ interests, as they enable students to join a specific elective field according to a specific job skill.
- Scale as it ensures the achievement of students’ efficiency and effectiveness, and helps them identify their tendencies and interests, and reveal their strengths, which enhances their chances of success in the future.
- Volunteer work designed specifically for students in line with the philosophy of activities in schools, and is one of the graduation requirements; which helps to promote human values, and build society (its development and cohesion).

- Bridging which enables students to move from one path to another according to specific mechanisms.
- Proficiency classes through which skills are developed and the achievement level improved, by providing enrichment and remedial mastery classes.
- The options of integrated learning and distance learning, which are built in the paths system based on flexibility, convenience, interaction and effectiveness.
- The graduation project that helps students integrate theoretical experiences with applied practices.
- Professional and skill certificates granted to students after completing specific tasks, and certain tests compatible with specialized organizations.

Accordingly, the computer science and engineering path as one of the updated paths at the secondary level contributes to achieving best practices by investing in human capital, and transforming the student into a participating and productive individual for science and knowledge, while providing him with the skills and experience necessary to complete his studies in fields that meet his interests and abilities, or to join the labor market.

Engineering Design is one of the main subjects in the Computer Science and Engineering Pathway, presented in a single comprehensive book. This book aims to provide an understanding of the concepts and technologies associated with Engineering Design, specifically focusing on 3D design and printing skills. The course introduces students to the importance of Engineering Design in various industries, such as product design and engineering. It covers the fundamentals of Engineering Design, including ideation, prototyping, 3D modeling, and 3D printing. The book also provides practical exercises and projects to reinforce students' understanding of the concepts covered by developing a physical prototype using 3D printing. The book emphasizes the importance of user-centered design, functional prototyping, and the use of digital tools in the Engineering Design process.

The Engineering Design book is characterized by modern engagement methods, which make students learn and interact with it through the various exercises and activities they provide. This book also emphasizes important aspects of Engineering Design education and learning, which are:

- The connection between the content and real-life problems.
- Diversity of ways to display engaging content.
- Highlights the role of the learner in the teaching and learning processes.
- Attention to the contents' structure and coherence.
- The skill of employing appropriate techniques in different situations.
- The ability to employ various methods in evaluating students in proportion to their individual differences.

To be on pace with global developments in this field, the Engineering Design book will provide the teacher with an integrated set of diverse educational materials that take into account the individual differences between students, in addition to educational software and websites, which provide students with the opportunity to employ modern technologies and practice-based communication; This solidifies its role in the teaching and learning process.

As we present this book to our dear students, we hope it will capture their interest, meet their requirements, and make learning this material more enjoyable and useful.

God grants success

بِسْمِ اللَّهِ الرَّحْمَنِ الرَّحِيمِ



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1. Principles of Engineering Design

In this unit, you will learn about the engineering design fundamentals and the job opportunities that exist. Then you will learn about the main measurements and material properties used in engineering design. You will then analyze the product lifecycle and learn about the technical aspects of project management. Finally, you will apply that knowledge to create a project plan for the development of a product.

Learning Objectives

In this unit, you will learn to:

- > Define what engineering design is.
- > List the job roles in engineering design.
- > Identify what design thinking is.
- > Distinguish the various design strategies.
- > Interpret measurements in engineering design projects.
- > Understand how materials are chosen in projects.
- > Classify different types of material properties.
- > Define what the product life cycle is and its stages.
- > Outline product engineering processes and best practices.
- > Analyze product lifecycle management processes and techniques.
- > Explain the pyramid of production systems.
- > Define what project management is.
- > Outline the characteristics that a project manager should have.
- > Construct a project management plan for the development of an engineering design product.

Tools

> GanttProject



Lesson 1

Introduction to Engineering Design

Link to digital lesson



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What is Engineering Design?

Engineering design involves building a system, component, or process to meet desired needs. It involves the creative implementation of scientific principles, and mathematical analysis to design, develop, and optimize a solution that meets the specific needs and constraints of a given problem or task. The design process often includes iterative prototyping, testing, and refinement cycles, which may involve collaboration with other engineers, scientists, and stakeholders. It is where engineers take a problem and, through a series of steps and processes, develop a solution that can be manufactured, tested, and used.

The stages of engineering design refer to the step-by-step process engineers follow when developing a new system, component, or process. The specific stages of the design process can vary depending on the specific project and the engineering discipline involved, but many engineering design processes include the following stages:

Design Process

A design process is a structured approach to solving a problem or developing a new system, component, or process. It is a series of steps that engineers or designers follow to take a project from the initial concept to the final implementation.

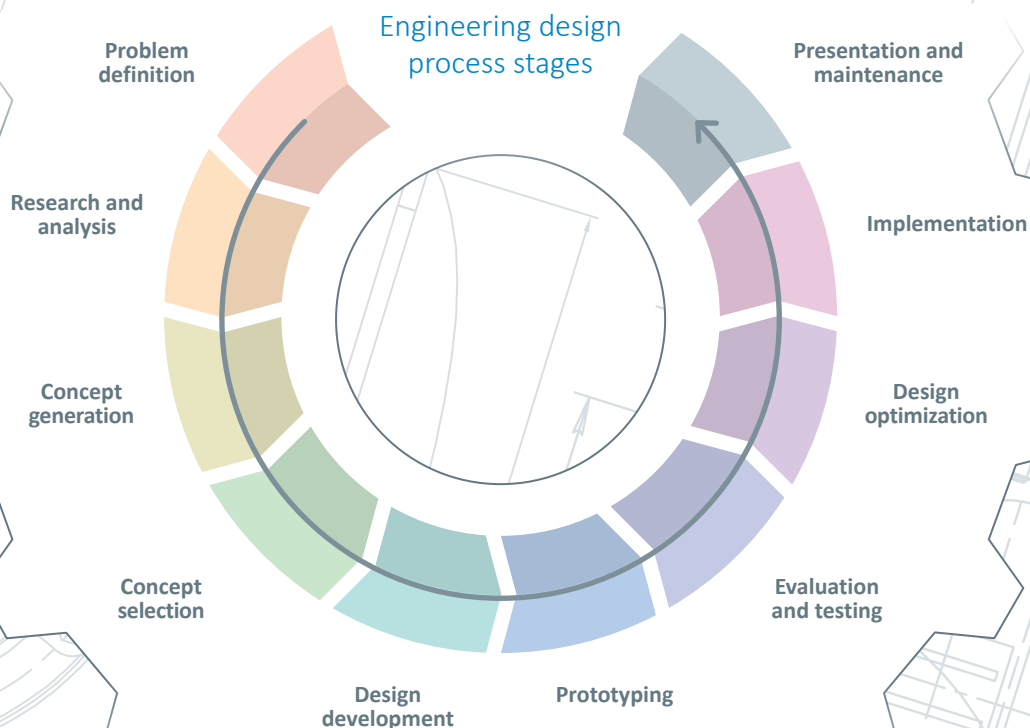


Figure 1.1: Engineering design process stages

Stages of the Engineering Design Process



1. Problem definition

Identifying and clearly defining the problem or need that the design will address.



2. Research and analysis

Research to gather information and data on the problem, including existing solutions and constraints.



3. Concept generation

Brainstorming and exploring multiple potential solutions, concepts and ideas for the design.



4. Concept selection

Evaluating and selecting the best concept based on feasibility, cost, and performance.



5. Design development

Develop detailed specifications and plans for the chosen concept, including drawings and 2D/3D models.



6. Prototyping

Building and fabricating physical or virtual prototypes of the design.



7. Evaluation and testing

Evaluating the prototype based on the design requirements, criteria, and constraints and testing its functionality and performance.



8. Design optimization

Making improvements and adjustments to the design based on testing and evaluation of results.



9. Implementation

Producing and implementing the final design, including manufacturing, installation, and training.



10. Presentation and maintenance

Monitoring and maintaining the design over time and evaluating its performance.

Job Roles in Engineering Design

The job roles in engineering design can vary depending on the specific field and the stage of the design process. However, some of the common job roles in engineering design include the following:

Design Engineer

A design engineer is responsible for creating and developing new designs, products, and systems. They use engineering principles and knowledge to create new designs that are safe, efficient, and functional.

Project Engineer

A project engineer is responsible for managing the design and development of a specific project. They work with engineers and designers to ensure the project is completed on time, within budget, and to the required specifications.

Systems Engineer

A systems engineer is responsible for complex systems' overall design and integration. They work with other engineers and designers to ensure that all components and subsystems work together effectively and efficiently.

Research Engineer

A research engineer is responsible for conducting research and development (R&D) to improve existing products and systems or develop new ones. They are responsible for gathering and analyzing data, testing new designs, and developing new technologies.

Manufacturing Engineer

A manufacturing engineer is responsible for designing and developing new manufacturing processes, equipment, and tools. They ensure that the production process is efficient and cost-effective and can produce high-quality products.

Quality Engineer

Quality engineers ensure that the design meets the quality standards and specifications. They work with other engineers and designers to identify and resolve issues and implement quality controls in the design process.

CAD Engineer

A CAD (computer-aided design) engineer is responsible for creating and maintaining the design's detailed technical drawings, 2D and 3D models, and specifications using computer-aided design software. They work closely with design and project engineers to create and update the technical drawings and models.

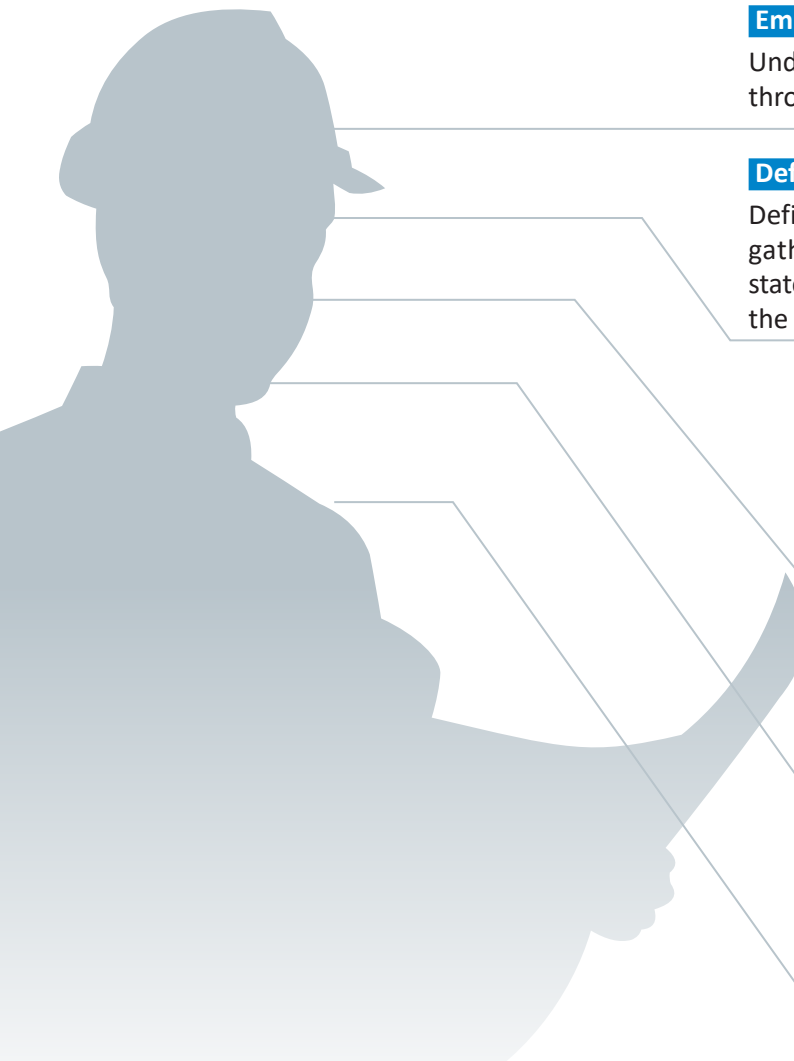
Testing and Evaluation Engineer

A testing and evaluation engineer is responsible for testing and evaluating the design to ensure that it meets the required performance, safety, and reliability standards. They conduct testing and analysis on the design and provide feedback to the design team to make any necessary improvements.

There are many engineering design job roles besides the ones mentioned here, and the exact roles and responsibilities can vary depending on the project and organization scale.

Design Thinking

Design thinking is a problem-solving approach to engineering design that emphasizes empathy for the user, and rapid prototyping. It is a human-centered design process that helps create innovative and effective solutions by understanding the users' needs, wants, and limitations. The design thinking process typically includes the following stages:



Empathize

Understand the user's needs, wants, and limitations through research, observation, and interviews.

Define

Define the problem by synthesizing the information gathered from the empathize stage. The problem statement is developed based on the user's needs and the desired outcomes.

Ideate

Generate a wide range of ideas to search for solutions through brainstorming, mind mapping, and other techniques.

Prototype

Create physical or virtual representations of the ideas generated in the ideation stage.

Test

Test the prototypes with users and gather feedback to improve the design iteratively.

Design thinking is a flexible and adaptive process that allows for iteration and improvement at any stage of the design process. It encourages experimentation, iteration, and rapid prototyping, which allows teams to test and validate assumptions, gather feedback, and make necessary adjustments. It is also a collaborative process that involves a multidisciplinary team of designers, engineers, researchers, and stakeholders working together to create solutions that meet the needs of the users.

Design thinking is used extensively in engineering design processes. It helps teams to create innovative and user-centered solutions by focusing on the needs of the users and encourages creativity and experimentation.



Design Strategies

Depending on each project's requirements and needs, various design strategies can be followed when developing an engineering design solution. Each design strategy follows a specific design process.

Linear Design

The linear design process is a step-by-step approach that involves moving through a series of stages in a linear, one-directional fashion, with little or no iteration. This approach is used in projects where the problem is well-defined and the solution is known, with fixed requirements. An example of this is designing a bridge, where each stage of the linear process must be completed before moving on to the next, with little room for iteration or changes to the design once construction begins.

The linear design process is less flexible than modern design processes such as Agile design, user-centered design, and design thinking, which are more iterative and allow for frequent testing and feedback.



Figure 1.2: Linear design in automotive industry

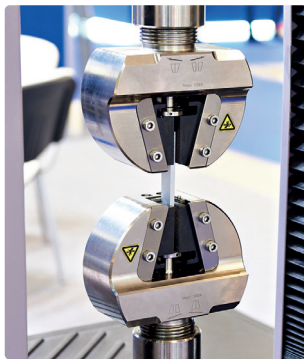


Figure 1.3: Quality testing during product manufacturing

Iterative Design

Iterative design is a process of refinement and improvement, where steps are repeated to make the design better. It allows for feedback and iteration at each step, and the process is cyclical in nature. An example of iterative design is the development of a drone, where each step from problem definition to prototyping and testing is repeated until the drone is ready for market, and feedback from users is used to improve the design continuously.

Iterative design is more flexible than linear design, allowing for frequent feedback and changes, and is commonly used in Agile development, user-centered design, and design thinking.

Inclusive Design

Inclusive design is an approach that considers the needs of all users, regardless of their abilities, age, gender, culture, or socio-economic status. It aims to create flexible and adaptable solutions to meet diverse needs, such as accessibility, usability, and universal design. An example of inclusive design is the development of a computer that has an ergonomic design and can be used comfortably by people with disabilities, the elderly, and children. The design of the computer includes features such as adjustable height, large fonts for writing, and text-to-speech capabilities to make it easier for users with different needs to interact with the computer.

Inclusive design engages with diverse users and stakeholders in an iterative, human-centered design process that fosters social inclusion and creates accessible solutions for a diverse population.



Figure 1.4: Public transport with an accessible ramp for persons with a physical disability



Figure 1.5: Formula 1 steering wheel is a characteristic example of user-centered design

User-Centered Design

User-centered design (UCD) involves understanding and addressing user needs through empathy, research, and iterative design. The UCD process begins with user research to gather data on user needs, which is then used to inform the design process, including the development of user personas and scenarios. The design concepts are tested with users, and feedback is used to improve the design iteratively. An example of UCD is the development of a car, where the designers conduct user research to understand the needs of drivers and passengers and then develop user-friendly features, such as intuitive controls, adjustable seats, and temperature control systems, to meet their needs.

Sustainable Design

Sustainable design is an iterative, multidisciplinary design approach that aims to create environmentally friendly and high efficiency in using resources solutions. It involves assessing the environmental impact of a design, identifying opportunities for resource efficiency, and considering the design's lifecycle, from sourcing materials to end-of-life disposal. An example of sustainable design for a physical product is the development of a solar-powered flashlight, which uses renewable energy sources to reduce waste and pollution and promote resource efficiency.



Figure 1.6: Products made of eco kraft paper



Figure 1.7: Modern wooden chair with ergonomic design

Ergonomic Design

Ergonomic design focuses on creating products and environments that are optimized for users' comfort, safety, and efficiency. The ergonomic design process involves assessing the physical and cognitive demands of tasks and users, identifying opportunities for improvement, and incorporating adjustable and customizable features. The computer mouse is an example of successful ergonomic design, as it was created to replace less efficient keyboard commands and designed based on users' natural hand movements for ease of use.



Exercises

1

Read the sentences and tick ✓ True or False.	True	False
1. Engineering design uses only mathematical analysis.	☐	☐
2. The prototyping stage comes after the generation of initial concepts.	☐	☐
3. After an engineering design project is completed, it is not optimized again.	☐	☐
4. System engineers focus on the communication and interoperability between other teams.	☐	☐
5. Design thinking considers the variety of needs different users might have.	☐	☐
6. Stakeholders do not participate in the design thinking process.	☐	☐
7. Linear design utilizes agile workflows.	☐	☐
8. Inclusive design focuses heavily on a project's research and analysis phase.	☐	☐
9. UCD is used exclusively in engineering design projects.	☐	☐
10. Ergonomic design focuses heavily on its users' cognitive and physical abilities.	☐	☐

2

Define what engineering design is.



3

[illegible]

4



5 List the stages of the design thinking process.

[illegible]

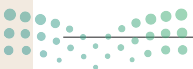
6 Compare the linear design and iterative design strategies.



7 Explain how inclusive design places the human user at the forefront of the design process.

8 Explain why UCD heavily emphasizes the feedback from the testing phase.

9 Explain why sustainable design is becoming more relevant nowadays.





Introduction to Measurements in Engineering Design

In engineering design, measurements determine the size, shape, and location of components and systems. These measurements are typically made using specialized instruments such as rulers, calipers, thermocouples, pressure gauges, load cells, and torque sensors. Additionally, computer-aided design (CAD) software is often used to create detailed models and simulations of engineered systems, which can be used to analyze and optimize their performance.

Table 1.1: Common units of measurement used in engineering design

	SI Units	US Units
Length	meters (m), centimeters (cm), millimeters (mm)	inches (in), feet (ft)
Mass	kilogram (kg), grams (g)	pounds (lb)
Time	second (s), minute (min), hour (hr)	second (s), minute (min), hour (hr)
Temperature	degree Celsius ($^{\circ}\text{C}$)	degree Fahrenheit ($^{\circ}\text{F}$)
Pressure	pascal (Pa)	pounds per square inch (psi)
Force	newton (N)	pounds-force (lbf)
Power	watt (W)	horsepower (hp)
Energy	joule (J)	watt-hour (Wh)

It is important to note that different countries and industries may use different units, and some units may be more appropriate for a specific application than others. For example, the International System of Units (SI) is widely adopted in many regions across the world including KSA, while the US customary unit is adopted in the USA. Furthermore, the context of the problem or application can dictate the best unit to use. For example, Celsius is more commonly used for temperature measurement in electronic devices than Fahrenheit. Table 1.1 illustrates the different units of measurement between the SI and US systems.

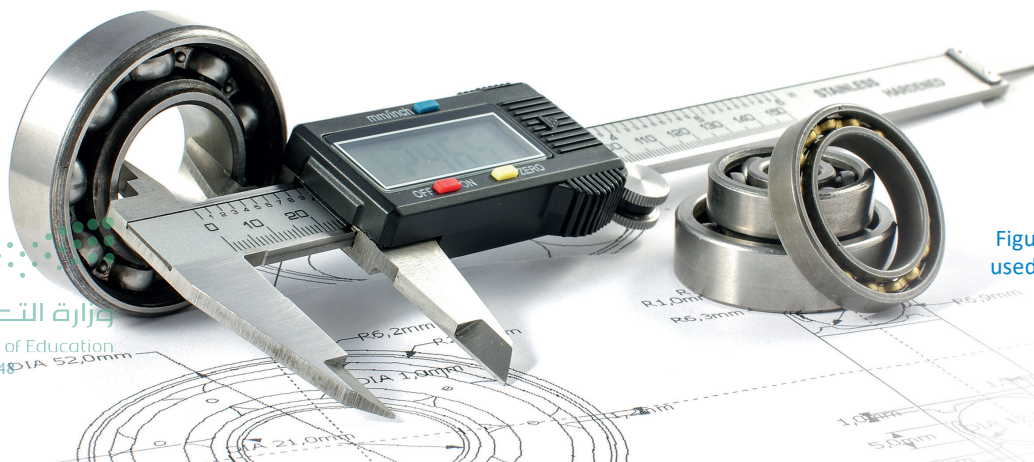


Figure 1.8: Electronic caliper is used for precise measurements

When working with units of measurement, engineers do not use singular units directly. They use multiples and submultiples of that unit. For example, mm or nm units for measuring relatively small distances. Table 1.2 illustrates the multiples and submultiples most commonly used with SI units.

Table 1.2: Multiples and submultiples most commonly used with SI units

Prefix	Exa	Peta	Tera	Giga	Mega	Kilo	Hecto	Deca	Deci	Centi	Milli	Micro	Nano	Pico
Symbol	E	P	T	G	M	k	h	da	d	c	m	μ	n	p
Multiplication factor (10 ⁿ)	18	15	12	9	6	3	2	1	-1	-2	-3	-6	-9	-12

Using Measurements in Engineering Design

Engineers typically use a combination of manual calculations and specialized software tools to make measurements and perform calculations in the design process. While some calculations may be done by hand, many are complex and require specialized software tools to perform them efficiently and accurately. For example, computer-aided design (CAD) software is widely used in engineering to create detailed models and simulations of engineered systems, which can be used to analyze and optimize their performance. Finite element analysis (FEA) software is also commonly used to simulate the response of structures and materials to various loads and conditions. These software tools can automate many calculations, provide visualizations of complex systems, and perform simulations to help engineers optimize the design of a product or system. Engineers rely on these tools to make accurate and efficient calculations, which is crucial for the design process.

It is worth noting that using precise, and accurate measurements is a critical aspect of engineering design and can greatly influence the success of a project or product. However, some complications must be considered when working with measurements, such as measurement errors and uncertainty that the tools are calibrated before using them in the measurements, and environmental conditions. Engineers must pay attention to these factors and use appropriate tools and techniques to ensure accurate and reliable measurements. For example, home weight scale with an inaccuracy of 1% from its 100 Kg range might provide a wrong reading of your weight by about 1 Kg. Table 1.3 illustrates the advantages and considerations of using accurate measurements in an engineering design project.

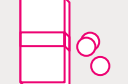
Table 1.3: Advantages and considerations of using accurate measurements

Advantages	Considerations
Allows precise and accurate characterization of components and systems.	Units of measurement must be carefully selected and consistent throughout the design process.
Helps identify and quantify design constraints and requirements.	Measurement errors and uncertainties must be evaluated and minimized.
Enables optimization and analysis of design performance.	Measurement equipment and techniques must be properly calibrated and maintained.
Facilitates communication and collaboration among members of the design team.	Complex systems may require multiple types of measurements and specialized equipment.
Allows computer-aided design (CAD) and simulation software to analyze and optimize the design.	Measurements must be made in an appropriate environment and under controlled conditions.

Introduction to Materials in Engineering Design

In engineering design, the properties of materials play an important role in determining the performance and suitability of a particular material for a specific application. Materials selection is a crucial step in engineering design, and engineers consider material properties to determine the best material for a specific application and design. Table 1.4 illustrates engineers' most common considerations when choosing the materials for their projects.

Table 1.4: Considerations when choosing materials

	Consideration	Description
	Mechanical properties	Mechanical properties such as strength, stiffness, Young's modulus (Elastic modulus), ductility, and toughness determine the material's ability to withstand loads and deformations.
	Physical properties	Properties such as density, melting point, thermal expansion, and electrical and magnetic properties determine the material's suitability for specific environments and applications.
	Chemical properties	Properties such as corrosion resistance, flammability, reactivity, toxicity, and biocompatibility determine the material's suitability for contact with humans or the environment.
	Cost	The cost of the material, including the cost of procurement, processing, and manufacturing.
	Availability	The availability and readiness of the material for the specific application, including supply chain and delivery time.
	Recycling and disposal	The environmental impact of the material, including the ease of recycling or disposing of the material at the end of its life.
	Standards and regulations	Compliance with relevant standards and regulations, such as safety, environmental, and industry-specific standards.

Types of Material Properties

Mechanical properties

Mechanical properties define a material's behavior when subjected to an external load. Table 1.5 illustrates the most common mechanical properties of materials used in engineering design.

Table 1.5: Mechanical properties of materials

Property	Description
Young's modulus (Elastic modulus)	A measure of a material's resistance to elastic deformation under load.
Tensile strength	A measure of a material's resistance to breaking under tension.
Yield strength	The stress at which a material begins to deform permanently.
Fatigue strength	A measure of a material's ability to withstand repeated loading cycles.
Shear strength	A measure of a material's resistance to shear stress.
Compressive strength	A measure of a material's resistance to compressive stress.
Toughness	A measure of a material's ability to absorb energy before breaking.
Ductility	A measure of a material's ability to deform plastically without breaking.
Hardness	A measure of a material's resistance to indentation or scratching.

Engineers must consider these properties and select a material with the appropriate mechanical properties for the specific application. For example, a material with high tensile strength and yield strength would be suitable for a component subject to high pulling forces. In contrast, a material with high ductility and toughness would be more suitable for a component subject to high-impact loads. Additionally, Hardness is also an important property for materials that will be subject to wear and tear. The selection of the right mechanical properties will ensure that the designed components have the strength, durability, and reliability to function properly and have a long life.



Thermal properties

Thermal properties are a set of characteristics that define the behavior of a material when it is subjected to temperature changes. These properties include thermal conductivity, diffusivity, specific heat, thermal expansion, and melting and boiling points. They are important to consider in engineering design as they can greatly influence the performance and suitability of a material for a specific application. Table 1.6 illustrates the most common thermal properties of materials used in engineering design.

Table 1.6: Thermal properties of materials

Property	Description
Thermal conductivity	The ability of a material to conduct heat.
Thermal diffusivity	A measure of the rate at which a temperature change propagates through a material.
Specific heat	The amount of heat required to raise the temperature of a unit of mass of a substance by one degree.
Thermal expansion	The change in a material's length, area, or volume by changing its temperature.
Melting point	The temperature at which a solid material turns into a liquid.
Boiling point	The temperature at which a liquid material turns into a gas.

These properties are important when materials are used in high temperature environments or thermal insulation. For example, when designing a heat sink for a computer processor, thermal conductivity, specific heat, and thermal expansion are important properties to consider. The melting and boiling point is also crucial as the heat sink must withstand high temperatures without losing its integrity.

Chemical properties

Chemical properties define a material's behavior when exposed to different chemicals or environments. Table 1.7 illustrates the most common chemical properties of materials used in engineering design.

Table 1.7: Chemical properties of materials

Property	Description
Corrosion resistance	The ability of a material to resist corrosion or deterioration when exposed to various environments, such as air, water, or chemicals.
Flammability	The ability of a material to burn or ignite.
Reactivity	The ability of a material to react with other substances, such as chemicals or gases, to form new compounds.
Toxicity	The ability of a material to cause harm or injury to live organisms, either through direct contact or through the release of toxic substances.
Biocompatibility	The ability of a material to remain in contact with living tissue without causing adverse reactions or negative effects.

In applications where materials will be used in contact with humans or the environment, the choice of materials is critical. These properties are also important in manufacturing and disposal or recycling materials.

Electrical properties

Electrical properties define a material's behavior when exposed to an electric field. Table 1.8 illustrates the most common electrical properties of materials used in engineering design.

Table 1.8: Electrical properties of materials

Property	Description
Electric conductivity	The ability of a material to conduct electricity.
Electric resistivity	The ability of a material to resist the flow of electricity.
Dielectric constant	The ratio of a material's permittivity to the permittivity of a vacuum, indicating how the material affects an electric field.
Dielectric strength	The maximum electric field a material can withstand without breaking down.
Loss tangent	The ratio of energy lost to energy stored in a material when an alternating current is applied.

The electrical conductivity, resistivity, and dielectric constant are important in determining the electrical performance of a material. The dielectric strength is important in determining a material's suitability for high-voltage applications, and the loss tangent is important in determining a material's suitability for wireless communications applications.

Magnetic properties

Magnetic properties define a material's behavior when exposed to a magnetic field. Table 1.9 illustrates the most common magnetic properties of materials used in engineering design.

Table 1.9: Magnetic properties of materials

Property	Description
Magnetization	The ability of a material to become magnetized when exposed to a magnetic field.
Magnetic susceptibility	The ratio of the magnetization of a material to the magnetic field strength.
Magnetic permeability	A property that describes how a material responds to a magnetic field and how easily magnetic flux can pass through it.
Curie temperature	The temperature at which a material loses its permanent magnetic properties.



These properties are considered in applications where materials will be used in magnetic fields or electromagnetic devices such as motors, generators, and transformers. Magnetization properties, magnetic susceptibility, magnetic permeability, and electrical conductivity are important in determining the magnetic performance of a material. The Curie temperature is important in determining a material's suitability for high-temperature applications.

Materials Used in Engineering Design

Materials can be broadly grouped into several categories: metals, polymers, ceramics, composites, and natural materials. Each category has its own unique set of properties, advantages, and limitations that must be considered when selecting a material for a specific application. For example, metals are known for their high strength and durability, while polymers are known for their flexibility and ease of molding. Ceramics are known for their high hardness and thermal resistance, while natural materials are known for their natural look and feel.

Selecting a material for a specific application is a critical step in engineering design. It requires a thorough understanding of the properties and behavior of different materials. Engineers must consider the environmental, safety, and performance requirements of the product or structure and the cost and availability of materials to make an informed decision. Table 1.10 illustrates the categories of materials that are used in engineering design and example categories of materials are shown in figure 1.9.

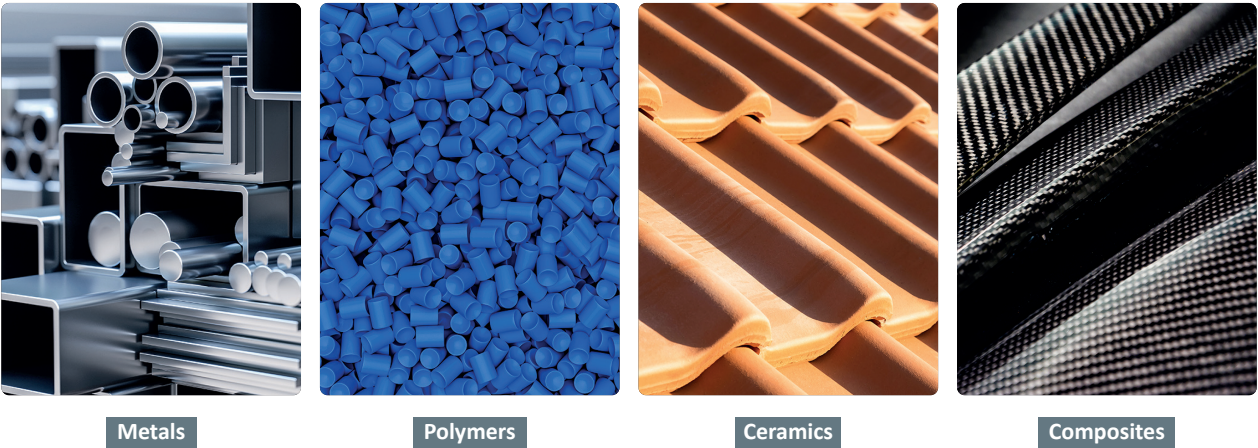


Figure 1.9: Categories of materials

Table 1.10: Materials in engineering design

Description	Example materials	Example applications
Metals		
A class of materials characterized by their metallic bonding, high thermal and electrical conductivity, and ability to be shaped.	Iron, steel, aluminum, copper, titanium.	Construction, automotive, aerospace, machinery, equipment, medical devices, implants.

Description	Example materials	Example applications
Polymers		
A class of materials characterized by their long chain-like molecular structure and ability to be molded or shaped.	Polyethylene, polypropylene, PVC, nylon, rubber.	Packaging, consumer goods, automotive, medical devices, electrical and electronic components.
Ceramics		
A class of materials is characterized by their high hardness, strength, and electrical and thermal resistance.	Alumina, silicon carbide, silicon nitride, zirconia.	Cutting tools, automotive parts, advanced ceramics, and electrical and electronic components.
Composites		
A class of materials composed of two or more different materials combined to create a new material with improved properties.	Fiberglass, carbon fiber, Kevlar.	Aerospace, automotive, sports equipment, construction materials, wind turbine blades.

Example



The Makkah Clock Tower is an architectural feat that stands as a symbol of Islamic culture and heritage. The tower's facade is covered with limestone, which is a natural and elegant material that gives the tower a distinctive appearance. The tower's windows and dome are made of glass, which is a transparent and modern material that allows natural light to enter the tower.



Exercises

1

Read the sentences and tick ✓ True or False.

	True	False
1. Horsepower (hp) is a unit of measurement of power.	☐	☐
2. Complex systems may require multiple types of measurements and specialized equipment.	☐	☐
3. Materials with low tensile and yield strength would suit a component subject to high pulling forces.	☐	☐
4. Thermal expansion is important when testing materials under extreme conditions.	☐	☐
5. Biocompatibility is a chemical property of materials.	☐	☐
6. The melting point is the temperature at which a material turns into a gas.	☐	☐
7. Curie temperature showcases where a material gains magnetic properties.	☐	☐
8. Ceramics are generally soft materials.	☐	☐
9. Material selection is important only for the economic viability of a product.	☐	☐
10. Composites are made to create materials with new properties.	☐	☐

2

Provide two units of measurement for each type of unit.



3

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4



5 Classify the most common considerations when choosing materials for an engineering design project.

[illegible]

6 Specify the difference between a material's toughness and ductility.

This image shows a single sheet of white paper with horizontal blue or grey ruling lines, typical of notebook paper. The lines are evenly spaced and run across the width of the page. There is no handwriting or other markings on the paper.

7 Distinguish a material's toxicity and biocompatibility and explain why they are important.

8 Analyze in what circumstances dielectric strength and loss tangent are considered when choosing a material.

9 List three categories of materials, describe them, and give some examples and applications.





What is the Product Life Cycle?

The product life cycle is a framework that describes the stages a product goes through, from its initial concept and development to its retirement or withdrawal from the market. The product life cycle concept is commonly used in marketing and strategic management to help companies plan for the life of their product and decide when to introduce new products, when to retire older products and how to maximize profits during the different stages. The stages of a product lifecycle are shown in the figure 1.10.

Stages of a Product Life Cycle

The product life cycle goes through the following stages:

- **Development:** This is the stage where a product idea is researched, developed, and tested.
- **Introduction:** The product is launched into the market, and the company begins to promote and sell it.
- **Growth:** The product gains acceptance in the market, and sales increase rapidly.
- **Maturity:** The product reaches its peak in sales and profits, and the market becomes saturated with similar products.
- **Decline:** Product sales decrease as it loses market share to new products or technologies.
- **Retirement:** The product is eventually phased out and removed from the market through discontinuation or replacement with a new product.

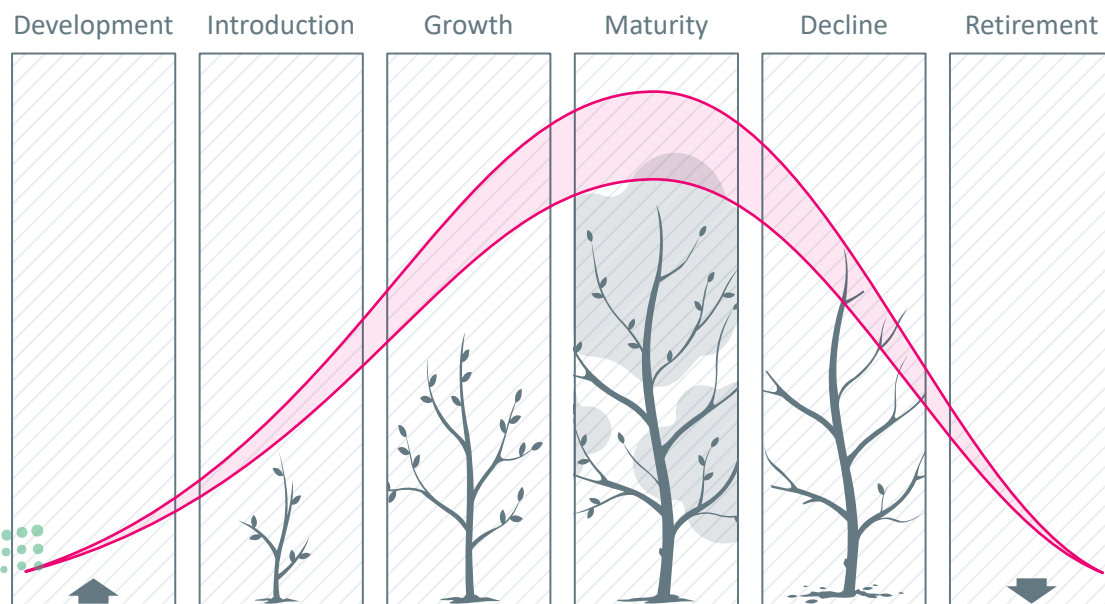


Figure 1.10: Stages of a product life cycle

What is Product Engineering?

Product engineering involves the process of conceptualizing and bringing a product to market through design and development. It is a multidisciplinary field that encompasses various aspects of product development, including mechanical engineering, electrical engineering, software engineering, industrial design, and materials science.

Product engineers are responsible for designing and developing products that meet customer needs and market requirements. They work closely with cross-functional teams, including designers, marketers, and manufacturing engineers, to ensure that the product is functional, reliable, and cost-effective.

Product engineering includes several key activities, such as:

- Conceptualizing and defining the product requirements.
- Designing the product and creating detailed specifications and engineering drawings.
- Conducting research and development to identify new technologies and materials.
- Creating prototypes and testing the product for functionality, performance, and reliability.
- Managing the product development process, including working with suppliers and manufacturers.
- Managing the product's life cycle, including maintenance and support.

Product engineering is a crucial part of the product development process, as it ensures that the final product meets customer needs and is manufactured cost-effectively and efficiently.

Product Engineering Phases

Product engineering generally includes the following phases:



1. Concept Development: This phase includes the initial ideation and conceptualization of the product. It includes market research, customer needs analysis, and feasibility studies to determine the viability of the product and to define the product requirements.



2. Design and Development: This phase includes the design and development of the product. It includes creating detailed specifications, engineering drawings, and prototype development.



3. Testing and Validation: This phase includes testing and validating the product to ensure that it meets the requirements and specifications set during the concept development phase. It includes testing the product design, performance, and reliability.



4. Manufacturing and Production: This phase includes the manufacturing and production of the product. It includes the creation of production tools and equipment and the assembly of the final product.



5. Maintenance and Support: This phase represents maintenance and support of the product after it has been released to the market. It includes addressing customer issues, providing technical support, and releasing updates or upgrades.



6. Retirement or Phase Out: This phase includes the end of the product's life cycle, either by reaching its end of life or being phased out for a newer model. This includes the processes of discontinuing the product and disposing of the product safely.



Product Engineering Best Practices

The following are some best practices for product engineering. Suppose that a company wants to build a car. Table 1.11 shows how the car company may apply the product engineering best practices:

Table 1.11: Application of engineering best practices for a car company

Best practice	Application
Understand customer needs and requirements	
Conducting market research, customer interviews, and focus groups can help product engineers understand what customers are looking for in a product.	The result of market research, customer interviews, and focus groups might conclude with an idea to build an electric car rather than a regular petrol-engine car.
Define the product requirements	
Clearly defined requirements ensure that the product is developed to meet the target market's needs. It also helps to identify potential issues early in the development process.	The product requirements, such as the car's driving range, top speed, charging time, and estimating the price required to meet customer needs.
Use a multidisciplinary approach	
Product engineering is a multidisciplinary field that requires the collaboration of various experts, such as mechanical engineers, electrical engineers, software engineers, industrial designers, and materials scientists.	A multidisciplinary approach with various experts is used to create the car's design and components that are optimized for performance, safety, and aesthetics.
Implement a robust testing and validation process	
This ensures that the product meets the requirements and specifications set during the concept development phase. It includes testing the product design, performance, and reliability.	A robust testing and validation process is implemented to ensure the car meets the requirements set during the concept development phase.
Leverage technology and innovation	
Product engineers should stay up to date with new technologies and materials that can be used to improve product performance, reduce costs, and increase sustainability.	New technology and innovation are leveraged to improve the car's performance, reduce costs, and increase sustainability.
Use project management methodologies	
A good project management approach will ensure that the project stays on schedule, within budget, and meets the goals set during the concept development phase.	Project management methodologies are used to balance time, cost and quality during the car development.
Continuously improve	
Product engineering is an iterative process. Once the product is launched, product engineers should continue gathering customer feedback, analyzing data, and improving the product.	Continuously improving the car's design, features, and performance based on customer feedback is necessary to meet evolving needs and expectations.

What is Product Life Cycle Management?

Product Life cycle Management (PLM) is a process used to manage the entire life cycle of a product from conception to retirement. It includes coordinating and managing all the data, documentation, and processes related to a product, including design, engineering, production, and support. PLM aims to improve efficiency and collaboration throughout product development and ensure that all stakeholders can access the most current and accurate product information.

Product Life Cycle Management Stages



Beginning Of life (BOL) stage

This phase includes the product's conception, design, and development. It is the phase where the product idea is generated and evaluated for feasibility, and the product requirements are defined. The BOL stage includes the following activities:

Market research

To understand the target market's needs and identify potential opportunities for the product.

Conceptualization

Creating a preliminary concept of the product and evaluating its potential for success.

Requirements definition

Identifying and defining the functional and non-functional requirements of the product.

Design and development

Developing detailed specifications, engineering drawings, and product prototypes.

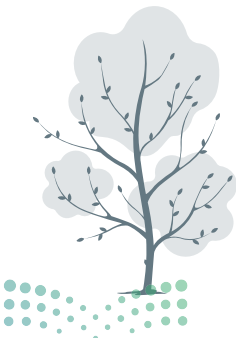
Testing and validation

Ensuring the product meets the requirements and specifications defined during the concept development phase.

Approval

Obtaining approvals from stakeholders such as customers and regulatory authorities.

This stage is critical to the product's success since it sets the foundation for the rest of the product's life cycle. A well-defined and feasible product will have a higher chance of success during the later stages of the product life cycle.



Middle Of life (MOL) stage

The product is manufactured, produced, marketed, and launched on a commercial scale in the middle of life (MOL) stage which includes the following activities:

Manufacturing and production

Creating the production tools and equipment and assembling the final product.

Supply chain management

Managing the flow of materials and components to support the production process.

Quality control

Ensuring that the product meets the required quality standards before it is released to the market.

Launch and commercialization

Releasing the product to the market and making it available for commercial use. This includes marketing, sales, and distribution activities.

Pricing and profitability

Establishing the pricing strategy and monitoring the product's profitability.

Market analysis

Analyzing the product's market performance and identifying improvement opportunities.

During this stage, the product is already in the market, and it is important to optimize the sales, costs, and supply chain to maximize profits. The product team will focus on maintaining and improving the product's performance and addressing any issues. This stage is also crucial to identify potential opportunities for product enhancements or new versions and the potential to expand into new markets.

End Of life (EOL) stage

The final phase of a product's development is when the product is phased out or reaches its end of life for discontinuing the product and disposing of it safely. This stage includes the following activities:

Product phase-out

Planning the phase-out of the product, including the timing and method of discontinuation.

Last-time-buy management

Managing the final orders and deliveries of the product to the customers.

Stock management

Managing the remaining product inventory and ensuring it is sold before discontinuation.

Retirement

Retirement of the product from the market and discontinuing its production and support.

Disposal

Disposing of the product and its components safely and in compliance with environmental regulations.

Post-retirement support

Providing support for the product for a limited time after its retirement.

During this stage, the product team will focus on managing the end of the product's life and ensuring a smooth transition to the next product or version. They will also work on recovering as much value as possible from the product before it is retired by selling off the remaining inventory. This stage is also important to plan for the end of any services or support provided for the product.



Product Life Cycle Management Techniques

Concurrent engineering

Concurrent engineering, also known as simultaneous engineering, is a product development approach that involves multiple teams working on different aspects of a product simultaneously. This approach is intended to speed up the product development process by reducing delays caused by working sequentially on different stages of the product development process.

Concurrent engineering involves a team-based approach in which engineers, designers, and other experts work together to develop a product from concept to launch. The teams simultaneously work on different aspects of the product, such as design, manufacturing, testing, and marketing. This approach allows for quick identification of potential issues and the ability to make changes early in the development process. Figure 1.11 compares the timelines of the "Normal" Engineering Plan and the Concurrent Engineering Plan. You will notice in this figure the overall time reduction introduced by the Concurrent Engineering technique.

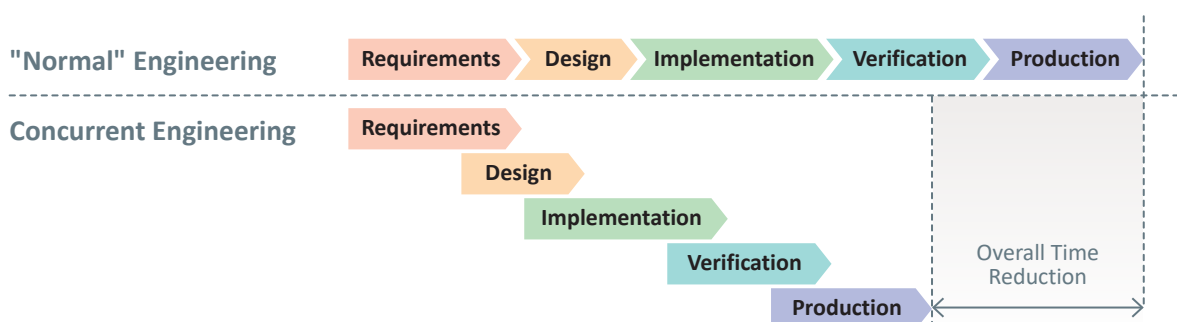


Figure 1.11: Reducing delays in development process with Concurrent engineering

Advantages of concurrent engineering include:

- Reduced product development time.
- Increased efficiency and collaboration among teams.
- Improved quality and reliability of the product.
- Reduced costs due to fewer design changes and reworkings.
- Early identification of potential issues and the ability to make changes early in the development process

Bottom-Up Design

Bottom-up design is an approach to product design and development that starts with the individual components of a system and works up to the overall system. The design process starts with a detailed design of the lower-level components, such as individual parts or subassemblies, and then integrates them into larger assemblies or subsystems. This process is repeated until the entire system is designed and integrated.

The main advantage of bottom-up design is that it allows for the design of the individual components to be completed before the overall system design is finalized. This approach allows for the optimization of individual components and can reveal any issues that may arise during the integration of the subsystems.

Top-Down Design

Top-down design is a product design and development approach that starts with the overall system and works to the individual components. The design process starts with defining the overall system architecture and then breaking it into smaller subsystems and components. The design of the individual components is completed after the overall system design is finalized.

The main advantage the top-down design is that it allows for a clear understanding of the overall system requirements before the design of the individual components begins. This approach allows for the optimization of the entire system and helps to ensure that the final product meets the needs of the customer or end-user.

Both Ends Against the Middle Design

Both Ends Against the Middle (BEAM) design is a product development approach that combines top-down and bottom-up design elements. It starts with the overall system and the individual components and uses an iterative process to develop the product by working on both levels simultaneously.

The main advantage of BEAM design is that it allows for the optimization of both the overall system and the individual components and helps to ensure that the final product meets the needs of the customer or end-user while being cost-effective, reliable, and easy to manufacture.

Front-loading Design and Workflow

Front-loading design and workflow is an approach to product development that emphasizes the importance of early planning, design, and development in the product development process. It aims to identify and resolve potential issues early in the development process before significant resources have been invested.

The front-loading approach is based on the idea that it is much more cost-effective to identify and resolve problems early in the development process rather than later on. The front-loading design approach reduces the time, cost and risks involved in the process of product development.

Design in Context

Design in context refers to considering the context in which a product will be used when designing it. This includes considering factors such as the environment, culture, user demographics, and the intended use of the product. The goal of design in context is to create products well-suited to the specific context in which they will be used that meet the intended users' needs.

Design in context is important in ensuring that products are well-suited to the specific context in which they will be used and that they meet the needs of the intended users. It can lead to products that are more usable, more accessible, and more sustainable. It is widely used in product design, especially in high-tech industries such as aerospace, automotive, electronics, medical, social, and environmental.



Pyramid of Production Systems

The pyramid of production systems is a framework used to classify and understand different levels of production systems. It is a hierarchical model representing the complexity and level of automation of production systems, starting with basic manual systems at the bottom and progressing to more advanced, automated systems at the top. The pyramid of production systems typically includes the following levels:

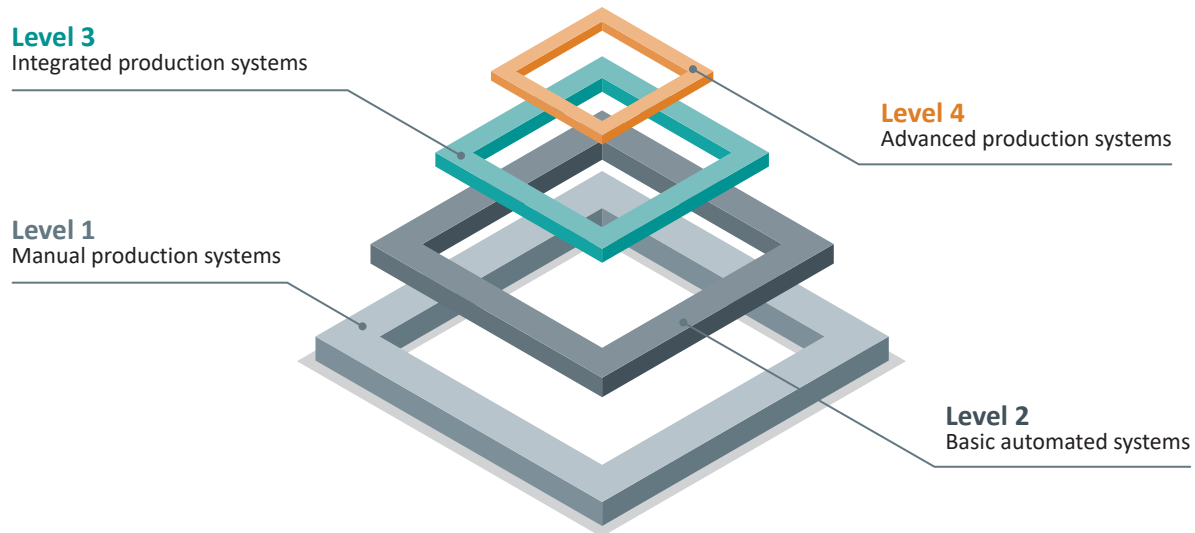


Figure 1.12: Levels of automation of production system

Level 1

Manual production systems: These systems rely on manual labor and are characterized by low automation and low productivity. They are typically used for simple and low-volume production tasks.

Level 2

Basic automated systems: These systems use basic automation techniques to automate certain aspects of the production process. They are characterized by higher levels of automation and productivity than manual systems.

Level 3

Integrated production systems: These systems use advanced automation techniques, such as computer-aided design (CAD) and computer-aided manufacturing (CAM), to integrate different aspects of the production process. High levels of automation and productivity characterize them.

Level 4

Advanced production systems: These systems use advanced technologies, such as robotics, artificial intelligence, and the Internet of Things, to optimize the production process. They are characterized by very high levels of automation and productivity.

For example, a furniture company produces handmade wooden chairs using manual production systems in a small workshop. As demand for their chairs grows, the company invests in a basic automated system by purchasing a machine to help cut and shape the wood more efficiently. Eventually, the company expands to an integrated production system by investing in a production line that uses advanced machinery to automate the assembly process and increase production volume. Finally, the company adopts an advanced production system by incorporating robotic systems to help with the finishing process and achieve higher levels of precision in the final product.

Exercises

1

Read the sentences and tick ✓ True or False.	True	False
1. The product life cycle is a process that includes only the initial research and design of a product.	☐	☐
2. The manufacturing phase of product engineering is concerned with how to assemble a product for mass production.	☐	☐
3. Engineers from various domains must collaborate with software engineers to produce greater quality work.	☐	☐
4. Product life cycle managers communicate with upper-level management as well.	☐	☐
5. The BOL stage includes quality control checks.	☐	☐
6. The EOL phase is concerned with the retirement of a product.	☐	☐
7. Concurrent engineering focuses on isolating engineering processes.	☐	☐
8. Products that are developed with front-loading design spend a lot of time on the early stages of planning and design.	☐	☐
9. Design in context is used for general-purpose products.	☐	☐
10. Level 4 of the pyramid of production systems is concerned with Industry 4.0 topics.	☐	☐

2

Summarize what the product life cycle is.



3

[illegible]

4



5

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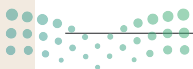
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This image shows a single sheet of white paper with horizontal ruling lines. The lines are evenly spaced and run across the width of the page. There are no margins, text, or other markings on the paper.

9 Describe how BEAM design combines bottom-up and top-down design.

This image shows a blank sheet of white paper with horizontal ruling lines. The lines are evenly spaced and extend across the width of the page. There are no margins, text, or other markings on the paper.

10 Explain the levels of the pyramid of production systems.

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Lesson 4

Project Planning

Link to digital lesson



www.ien.edu.sa

What is a Project?

A project is a temporary endeavor designed to achieve a specific goal or objective. Projects are unique, meaning they are not part of an organization's ongoing operations, but rather they are initiated to create a specific product, service, or result.

Projects have a defined start and end date, and they are typically constrained by a budget, a scope, and a timeline. They often involve multiple stakeholders, resources, and complex interactions between them. Project management is the discipline of planning, organizing, and managing resources to achieve project goals and objectives.

Examples of projects can include building a new bridge, developing a new software application, organizing a large event, conducting research, or launching a marketing campaign. Projects can be small or large, simple or complex, and can be found in almost every industry and field of work.

Project

A project is a series of activities or tasks to be completed within a specified time frame and within a specified budget in order to create a product or service.

Project Characteristics:

- It has a fixed timeline that specifies the start and end date of the project.
- Has a defined scope of work and clear objectives.
- Independent with a set budget and resources.
- It involves a series of sequential and interrelated activities.
- It faces risks and challenges that should be guarded against.

Project Planning

Project planning is the process of defining the scope, objectives, and tasks necessary to complete a project. It involves creating a road map that outlines the various activities, milestones, and resources needed to achieve project goals within a specified time frame.

Good design for any project requires that the project plan define the project's purpose, the resources required, the budget, and the timeline. It should also define the roles and responsibilities of the team members, the communication plan, risk management strategies, and the methods of tracking and evaluating progress.

Effective project planning helps to ensure that all team members have a clear understanding of the project's goals and requirements, and it allows them to work together more efficiently and effectively to achieve those goals. It also helps to identify potential risks and obstacles, allowing the project team to mitigate them proactively and prevent delays or other negative impacts on the project.

Project planning typically involves the following steps:



1. Defining the project scope: Defining the requirements of the project, the desired outcomes, and the stakeholders involved.

2. Developing a project plan: Creating a detailed project plan that outlines the tasks, resources, and timelines necessary to complete the project.

3. Identifying project risks: Identifying potential risks that may arise during the project and developing strategies to mitigate them.





4. Defining project roles and responsibilities: Gathering the team members involved in the project and their roles and responsibilities.



5. Setting project milestones: Defining specific points in the project where progress can be measured and evaluated.



6. Monitoring and controlling the project: Tracking project progress, identifying issues that arise, and taking corrective action as necessary.

Project planning is important for several reasons, including:

Clarity of objectives

Project planning helps to clearly define the project's objectives, including the expected outcomes, timelines, and budgets. This clarity ensures that all stakeholders are on the same page and can work together towards a common goal.

Resource allocation

Project planning helps to identify the resources required to complete the project, including personnel, equipment, and materials. This information allows for effective resource allocation, which can help to minimize costs and improve efficiency.

Risk management

Project planning helps to identify potential risks and develop strategies to mitigate them. By addressing potential issues before they arise, project managers can reduce the likelihood of delays, cost overruns, and other project failures.

The lack of a project management plan leads to lost time and poor performance. In order to avoid such situations, we have to organize and manage the project in the most effective and efficient manner. Effective project planning is essential for ensuring that a project is completed on time, within budget, and to the satisfaction of stakeholders. It helps to minimize risks and ensure that project goals are achieved.

SWOT Analysis

One possible technique to use for risk management in projects is SWOT analysis. The SWOT analysis produces a diagram that is a visual tool used to analyze a company, project, or product. It is divided into four sections: **Strengths**, **Weaknesses**, **Opportunities**, and **Threats**. Each section represents different aspects of the analysis. Strengths and Weaknesses refer to internal factors whereas Opportunities and Threats refer to external factors that the company cannot control.

- **Strengths** are the things that a company, project, or product is good at or has an advantage in. Strengths are internal.
- **Weaknesses** are the things that a company, project, or product struggles with or puts them at a disadvantage. Weaknesses are internal factors.
- **Opportunities** are external factors that a company, project, or product can take advantage of to achieve success.
- **Threats** are external factors that can negatively impact a company, project, or product.

Internal factors	External factors
Strengths	Threats
Weaknesses	Opportunities

Figure 1.13: Typical SWOT analysis diagram

SWOT analysis factors are summarized in figure 1.13.



By analyzing these four areas, a company can form a better understanding of its strengths, weaknesses, opportunities, and threats. This can help them make better decisions and develop more effective strategies to achieve success. A typical SWOT analysis diagram for a company is shown in figure 1.14.

	Strengths	Weaknesses
Internal factors	Established brand reputation and skilled employees	Limited budget for marketing and outdated technology
	Opportunities	Threats
External factors	Emerging market for product expansion	Competition from established players and changes in regulations that make it harder to operate

Figure 1.14: SWOT analysis example

What is Project Management?

Project management is the process of planning, organizing, and managing resources to achieve specific goals and objectives within a defined project scope, timeline, and budget. It involves coordinating and controlling various aspects of the project, such as scope, time, cost, quality, risks, communication, and resources, to ensure that the project is completed successfully.

The key components of project management include initiating the project, planning the project, executing the plan, monitoring and controlling the project, and closing the project. These processes involve identifying project goals, creating a project plan, allocating resources, monitoring progress, making necessary adjustments, and evaluating the project's outcomes.

Project Management

Project management is the process of planning, executing, and controlling resources to achieve specific goals within a defined timeline.

Effective project management requires a range of skills, including leadership, communication, problem-solving, decision-making, and risk management. It also involves working closely with project stakeholders, including clients, sponsors, team members, and suppliers, to ensure that their needs and expectations are met. Project management is used in a wide range of industries and fields, including construction, engineering, software development, marketing, healthcare, and education, to name a few. By implementing project management best practices, organizations can improve their efficiency, productivity, and overall success in completing projects.

Project management enables the following benefits:

- Saving time and effort by focusing on priorities.
- Overcoming difficulties and reducing the chances of failure.
- Achieving a high degree of follow-up.
- Adapting to variables.
- Effectively managing the budget allocated to the project.

Project management provides the general framework for control, and by using software utilities (such as Gantt Project) and other technologies, the work team can be led to achieve the desired goals on time and within budget.

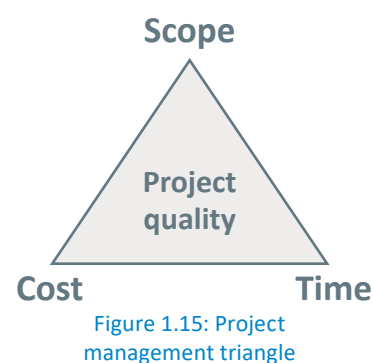
Project Management Triangle (Scope-Time-Cost)

To ensure the success of the project, the changes that may occur in the main determinants associated with it must be studied, understood, and dealt with in order to achieve the desired quality of the product or service. These determinants are: (scope, time and cost) as they are illustrated in Table 1.12.

Table 1.12: Project management parameters

 Scope	The tasks required to achieve the project objectives.
 Time	The timeline for the project to create the product.
 Cost	Project budget.

These determinants constitute the project management triangle, which is a model that helps project managers optimize outcomes, by maintaining a balance between these determinants and monitoring changes that occur during the course of the project and knowing the effect of increasing or decreasing each determinant on the rest of the determinants and its final impact on quality. For example, if the scope of work to be completed increases during the project, this will inevitably cause an increase in either the completion time or the required cost, or both. These determinants may seem simple, but each of the three points of this is worth exploring in more depth.



Scope

Scope refers to all the work and activities that are carried out to create the desired product or service. If we cannot control the scope of the project, we will not be able to deliver it on time or within budget. It is important to set priorities so that we can plan and allocate resources effectively. We have to make sure that we manage the prerequisite tasks that enable our project to evolve smoothly, in this way, we can assign important project tasks to the right people and enable collaboration on the task level itself.

Time

Time is calculated by writing down all the tasks required to move from the beginning of the project to its end, then the time required for each task and the priorities of the tasks are determined.

Cost

The financial cost of the project depends on several variables, and it has many examples such as the human resources required, tools and equipment used, raw materials, etc.

The costs are divided into two parts:

1. Fixed costs such as: workers' salary costs, rental costs...
2. Variable costs such as: electricity and water costs, costs of materials used in production...

Maintaining Balance in the Project Management Triangle

When you manage a project and find an issue that may affect the quality of the project or its goals, you should:

First

Determine the location of that problem from the elements of the three determinants, what is fixed and what is variable. Is the problem related to the time available to implement the project?, Or is it related to an increase in the size and scope of the project? Or maybe, is it related to a lack of the required funds and resources?

Second

Make the possible adjustments to achieve the necessary balance in order to reach the desired quality of achieving the project objectives.

What is a Project Manager?

A project manager is a professional responsible for leading a team and managing a project from start to finish. They are accountable for the overall success of the project, ensuring that it is completed on time, within budget, and to the satisfaction of stakeholders.

The role of a project manager involves a range of responsibilities, including:

Planning the project

Defining project goals, objectives, scope, and requirements; creating a project plan and timeline; identifying and allocating resources; and developing a communication plan.

Executing the project

Managing and coordinating project team members and resources; monitoring progress against the project plan; resolving issues and conflicts; and ensuring that project deliverables meet quality standards.

Monitoring and controlling the project

Tracking project progress and identifying variances from the plan; making adjustments to the project plan as needed; managing project risks; and communicating with stakeholders about project status.

Closing the project

Conducting a final project review; obtaining sign-off on project deliverables; closing out contracts and agreements; archiving project documentation; and conducting a lessons learned session.

A successful project manager must possess a range of skills, including leadership, communication, problem-solving, decision-making, and risk management. They must also have a deep understanding of project management methodologies and tools, as well as the industry and field in which they are working.

Project Manager

The project manager plays a key role in the project, as he/she is primarily responsible for its successful completion. The manager's job is to ensure that the project progresses within its time frame and within its budget while achieving its objectives. It is a big plus for the project manager to have enough experience and background related to the project.

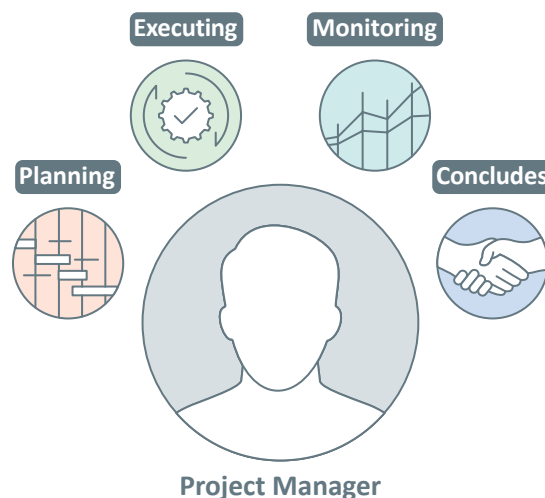


Figure 1.16: Responsibilities of a Project manager

Project manager duties

- Developing a project plan.
- Recruitment of the project team.
- Leading and managing the project team.
- Developing the project schedule and identifying each phase.
- Assigning tasks to project team members.
- Providing regularly updated reports to senior management.

It is the project manager's responsibility to define the role of each team member and to ensure that they work together as a team. The project manager must motivate the team, listen to everyone's ideas, and ensure that all team members stick to the set work schedule.

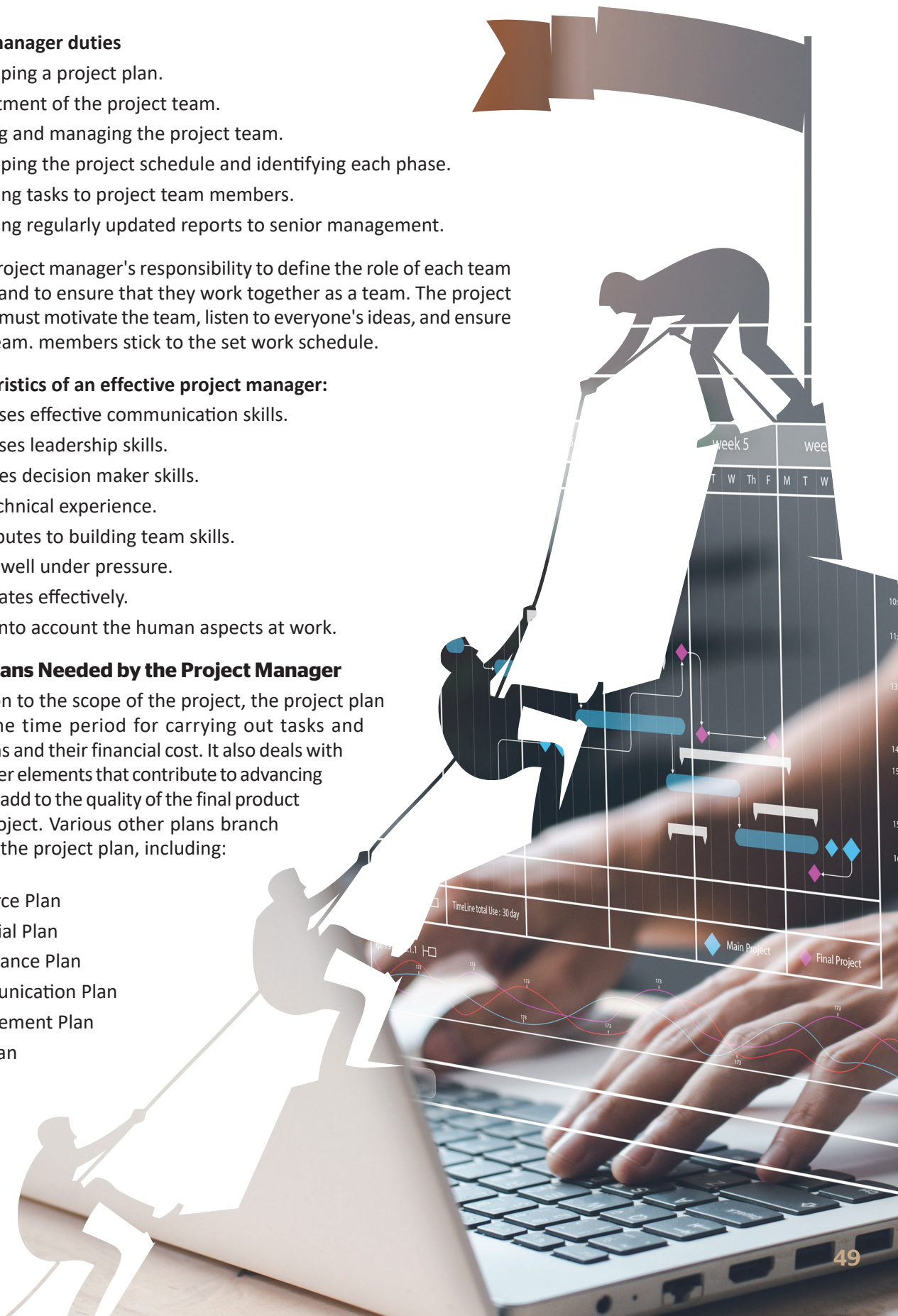
Characteristics of an effective project manager:

- Possesses effective communication skills.
- Possesses leadership skills.
- Possesses decision maker skills.
- Has technical experience.
- Contributes to building team skills.
- Works well under pressure.
- Negotiates effectively.
- Takes into account the human aspects at work.

Other Plans Needed by the Project Manager

In addition to the scope of the project, the project plan details the time period for carrying out tasks and operations and their financial cost. It also deals with many other elements that contribute to advancing work and add to the quality of the final product of the project. Various other plans branch out from the project plan, including:

- Resource Plan
- Financial Plan
- Acceptance Plan
- Communication Plan
- Procurement Plan
- Risk Plan



Project Scope Planning

The project scope planning process involves identifying all the work and tasks through which the project can be implemented, and it consists of:

Determining the Scope of the Project

At this stage, the main tasks that should be carried out to implement the project are determined. For example, the process of hiring a person for a particular job goes through several stages:

- Job advertisement.
- Choose the candidate.
- Interview the candidate.
- Submit an official job offer to the candidate.



Figure 1.17: Determining the scope of the project

Breaking the Project into Smaller Tasks

The idea of teamwork is to divide the work team into smaller groups that carry out the subtask assigned to them.

For example, the engineering design process for building a house includes the following tasks:

- Creating a draft of the architecture.
- Preparation of construction documents.
- Agreeing on the architectural plan.

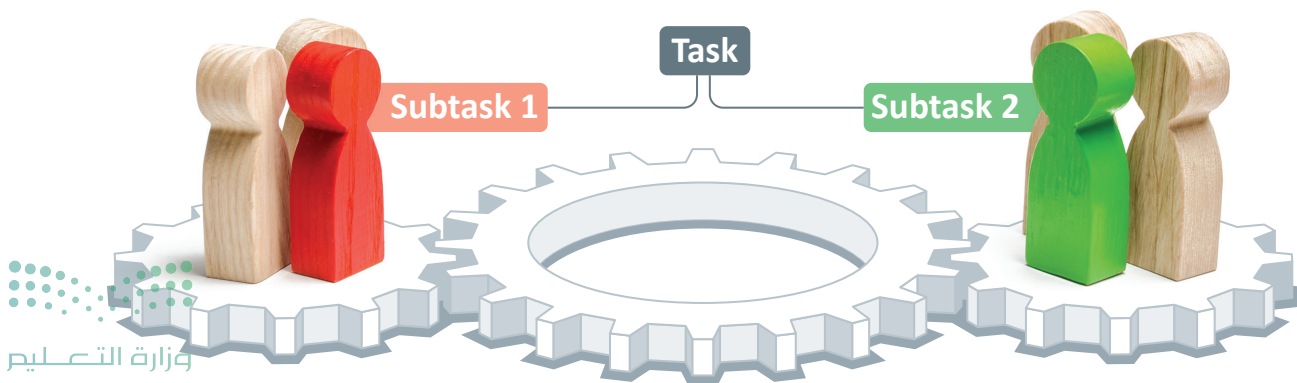


Figure 1.18: Breaking the project into smaller tasks

Timeline

Estimating Time

The time factor is one of the important determinants in the project management triangle, and time planning comes immediately after the completion of defining the scope of the project, its main activities and the tasks that it includes.

The project manager should estimate the time required to complete each task in collaboration with the project team, and this may require a lot of negotiation especially if the project has deadlines for delivery. For example, each member of the house construction team must agree on an estimated time for each activity or task, so the project manager, heavy machinery operator, architect, builders, and staff must agree on the amount of time allotted to their task. If it is difficult to estimate how long an activity might take, then the best and worst case scenarios are estimated and a compromise is reached between the two.

Prioritizing Tasks According to Needs

At this stage, we need to:

- Put the tasks in a logical sequence.
- Estimate the duration of each task.
- Use clear documentation to help us develop a project schedule.

Arranging and scheduling tasks

After creating the list of tasks required to complete the project, the project manager needs to consider how they are interrelated. He decides which tasks form the basis of the project and which must be started immediately and completed before moving on to the next tasks.

For example, we can't predesign, furnish or plan a home's equipment if the architectural plan is not complete, or we can't build a roof if the first floor isn't finished. Figure 1.19 shows basic matrix prioritization.



Figure 1.19: Basic tips to prioritizing tasks

Methods for Prioritizing Tasks

Here are two methods you can use to prioritize your project tasks:

ABC analysis method

This way of doing business has long been used to classify big data into groups. These groups are usually marked with "A-", "B-" and "C-" tags followed by the name. Activities are classified according to these general criteria:

- A- Important and urgent tasks.
- B- Important and non-urgent tasks.
- C- Non-important and non-urgent tasks.

Each group is then prioritized, and for further prioritization, some choose to reclassify all items in group "B" to "A" or "C". An ABC analysis can include more than three groups.

Eisenhower method

All tasks are evaluated according to the following criteria: important/non-important, or urgent/non-urgent, and are divided into quadrants accordingly.

In this method, the unimportant and non-urgent tasks are placed last in priority, the important and urgent tasks are prioritized to be done immediately by the project manager, while others are relegated to do the unimportant and urgent tasks, and the important and non-urgent tasks are set a finish date and are scheduled by the project manager as well. An example of the Eisenhower method is shown in figure 1.20.

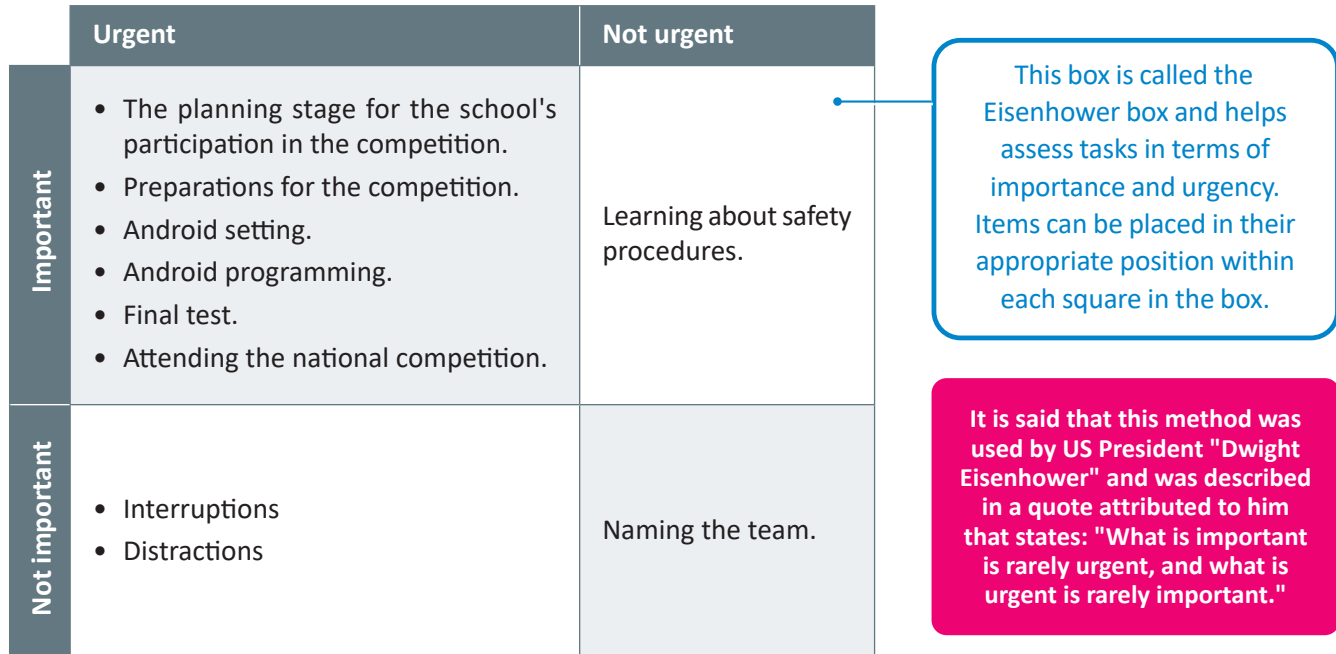


Figure 1.20: Eisenhower method

Determining Project Milestones and Deadlines

What are Project Milestones?

In project management, any project milestone is a major event that requires special attention. For example, in the project to participate in the National Robot Competition, the process of building the robot, for example, is considered a basic milestone in the project, and the process of completing the programming of the robot in its final form is considered a second milestone in the project.

Milestone

A milestone in the project is a point that represents a major event in the project life cycle, and when the milestone is reached, the project moves to the next stage.

What is the Deadline?

A task or project deadline is the latest time or date by which the task or project can be completed.

Why is the Deadline important?

Setting a deadline is very important in everything we do in our life, it is simply a way to handle time wisely due to its finiteness. Deadlines, for example, are similar to our exam dates. Suppose we need to finish studying a course by the exam date. If we do not plan and stick to our schedule, it will be difficult to complete our studies on time, which may lead to failure in the exam and perhaps a full academic year's delay.

Deadline Features:

- Sets a specific schedule for productivity.
- Improves discipline and work ethic.
- Constantly brings us closer to our goals.
- Provides a sense of accomplishment.
- Reduces procrastination and indecision.

Points to Consider When Setting a Deadline:

- Deadlines must be realistic. And balanced to avoid work stress and resource depletion.
- A margin for error or delay in project time estimation.
- Informing employees and workers of the time plan for project implementation and reminding them of it periodically.
- Ensuring that the project resources are sufficient to complete on time.

Resource Management

Resource management refers to the process of efficiently and effectively allocating and utilizing available resources in order to achieve specific goals and objectives. This can include both tangible resources such as people, money, equipment, and materials, as well as intangible resources such as time and expertise.

Effective resource management involves careful planning, coordination, and optimization of available resources to ensure that they are being used in the most efficient and effective way possible. This can involve identifying the needs and requirements of a project or organization, prioritizing tasks and activities, allocating resources to specific tasks, monitoring resource usage, and making adjustments as needed to ensure that resources are being used to their fullest potential. Resource management can be a critical factor in the success of any project or organization. Poor resource management can lead to inefficiencies, delays, cost overruns, and other problems that can negatively impact project outcomes. On the other hand, effective resource management can help to ensure that projects are completed on time, within budget, and to the desired quality standards.

Resource and project management are used to schedule and plan work activities. They make the overall project planning process more efficient and can help us achieve our goals. Proper implementation of enterprise resource management techniques can help us use the resources in the organization more effectively.

Project Cost

Cost management is very important in project management. To better understand this, we will learn the components of cost management, cost estimation and its challenges, types of resources, as well as the roles and tasks that are assigned to cost management.

There are two types of costs for any project:

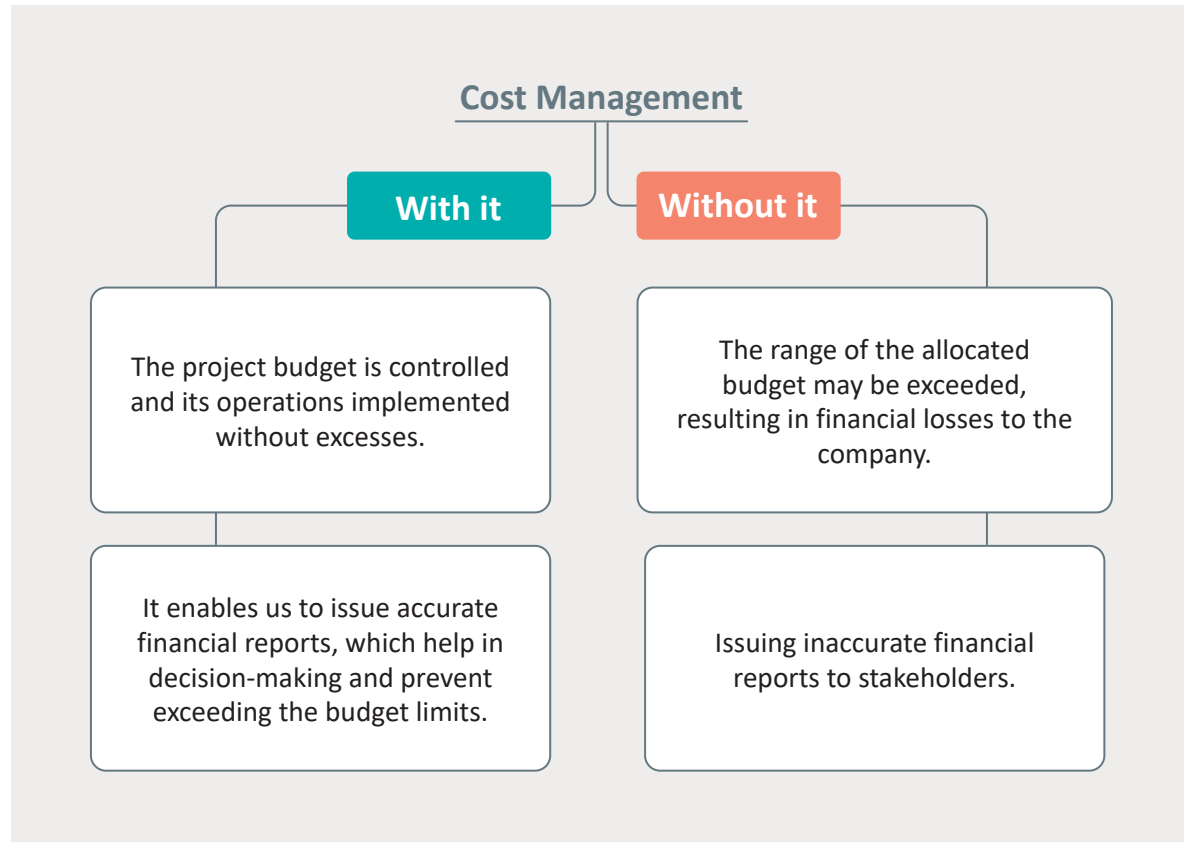
Direct costs:

These include labor expenses, materials and tools.

Indirect costs:

These include operating expenses, such as electricity, Internet, and fuel.

Importance of Cost Management:



Elements Taken into Account in Project Cost Estimation:

Human Resources:

The cost of wages for team members and the duration of work on the project.

Materials and Equipment:

The cost of purchasing the tools, software, equipment cost, legal permits, and the like.

Facilities:

Rents paid for workspace.

Suppliers:

Third-party contractors or subcontractors.

Challenges and risks:

The project may deviate from the planned path due to the occurrence of some problems that may increase the cost, and therefore precautions should be taken during the estimation process.



Cost Estimation

Cost estimation in project management is the process of forecasting the financial and other resources required to complete a project within the scope specified for that project.

Challenges facing the cost estimation process

The cost estimation process is not easy, and it may be inaccurate at times, especially in modern technological projects. Table 1.13 illustrates some of the problems facing the cost estimation process:

Table 1.13: Challenges in the cost estimation process

Expediting cost estimation	In many cases, the cost is estimated before the requirements for the project are fully clear, and therefore the cost should be reviewed more than once during the course of the project to avoid expenditure overruns.
Inexperience of cost estimators	Experience plays an important role in the accuracy of cost estimation. The presence of data from previous or similar projects contributes to the accuracy of the estimation.
Bias of the human element to reduce the cost	The project manager may tend to estimate the cost less than it actually is, for example, he may not be fully aware of the exact technical aspects of the project, so it is important to involve project team members in the cost estimating process to benefit from their expertise in the technical aspects of each member.
Management and stakeholder pressures to reduce cost	Departments often put pressure on the project manager to reduce costs, and this pressure can lead to cost estimation errors.

Resource Mapping

The implementation of project tasks requires a lot of resources, as those resources can be equipment, facilities, financing, or human resources (employees for the project) required to accomplish the project tasks. Thus, the lack or insufficiency of some of these resources is an impediment to the completion of project tasks. For example, in a home construction team, we cannot create the engineering plan for a house without a project manager and an architect.

Resource Types

Storeable resources:



They are tangible resources that can be stored or converted into cash when needed, such as tools, machinery, and equipment.

Non-storable resources:



They are intangible resources, and their financial value is difficult to estimate, but they contribute to the implementation of project operations and product quality, such as licenses, trademarks, the reputation of the company executing the project, and others...

Resources and Successful Project Management

The allocation of limited resources depends on the priority given to each project task. The priorities of these resources are calculated using the Critical Path Method, which you will study in more detail later. The members of the home construction team who work on the project are vital resources for this project, and the goal is to create the most efficient schedule possible.

For example, a home construction team can contain up to three builders, allowing the duration of the project to be reduced as much as possible.

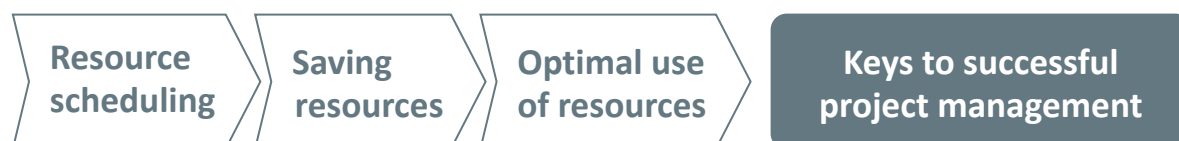


Figure 1.21: Efficient use of resources

Human Resources (HR)

Human resource management is considered one of the most important departments in business institutions and companies, as it focuses on the human element that will carry out the tasks and activities of any institution.

Working as a Team

Benefits of teamwork:

- Promotes creativity and learning.
- Mixes the strengths of the team members, creating a kind of complementarity.
- Promotes confidence building.
- Teaches conflict resolution skills.
- Promotes a sense of belonging.

Division into Sub-Teams

To do work effectively, it may be necessary to divide the work team into sub-teams, as forming smaller work teams means dividing the work into smaller and simpler parts. Each sub-team performs a task within a certain period of time, for example the task of preparing house construction designs with interior decoration pre-design. In this way, tasks that are not related to each other can be completed at the same time by different sub-teams thus getting work done in the least possible time.

The Most Important Criteria for Selecting a Work Team

Specialization and previous experience:

It is advisable to select team members who are specialized in their areas of project work and have previous experience.

Team member skills:

Selection of team members with diverse and integrated skills that serve the nature of the project.

Personal characteristics of team members:

Taking into account the personal aspects of team members such as commitment, enthusiasm, willingness to work, and other desirable traits.

Project Team

The project team is a team selected to carry out specific project.ect.



Points to be Considered for Successful Teamwork

The project team is a dynamic entity with relative autonomy and strong internal communication that requires:

- Diversity of disciplines and talents and their integration.
- Balance in distributing tasks to members, each with its own characteristics.
- Effective participation of members in decision-making within the team.
- The existence of effective communication channels between the project manager and team members, as well as with other parties involved in the project.
- Providing a work environment that allows expression of opinion and constructive criticism and generation of ideas and proposals that contribute to raising the quality of performance in the project.
- Resolve differences and conflicts between members quickly, maintain team unity, and focus on achieving project goals.

Relationships

Most project tasks are related to each other, for example, one task must be completed to start other tasks, that is, there are tasks that depend on other tasks. Dependencies are the relationships between tasks, a multitasking task may have a predecessor and a successor. A task dependency is a relationship in which a task or milestone is fully or partially dependent on other tasks being performed, it may also be referred to as a logical relationship. A logical relationship can be a dependency between project tasks or between project milestones and tasks.

Understanding task dependency in project management is an essential element in managing the critical path of a project, for example, during the construction of a building, we cannot prepare construction documents if the engineering drawing of the building is not completed, and the construction team cannot agree on the engineering drawing if the construction documents are not prepared.

In project management, there are four possible types of logical relationships:



Finish to Start

A task must be completed before the next task can be started.



Finish to Finish

It is required that one task ends in order for another task to finish (both tasks finish).



Start to Start

You must start one task in order for another task to start (both tasks start together).



Start to Finish

You must start one task before the other task can finish.

Risk Management Plan

This plan aims to minimize any potential problems arising from risks that may adversely affect the completion of the project. Some of the risks in the business are if a construction worker has an accident while working on building house, for example, or the robot battery stops working during a robot competition, so it is important to prioritize the risks and define a set of actions to reduce the possibility of a risk and of course limit its impact on the project if it occurs.

The following are the most prominent risks that most projects may face:

Types of Risks and Actions to Mitigate them

- **Inaccurate project planning:** Review and update the project plan periodically.
- **Constant changes in scope of work:** Hold periodic meetings with stakeholders and the project team and agree on a clear mechanism for modifying or changing the scope of work.
- **Absence or replacement of the team leadership or its members:** Develop a backup plan that includes replacements for team members, especially those on whom the success of the project depends.
- **Miscalculation of project cost:** Continuous review of the financial plan and the allocation of reserve funds from the project budget to contain risks or contingent costs.
- **Miscalculating the time required to finish the project:** Reviewing the project schedule and setting up backup procedures to complete the work in a timely manner, such as increasing human resources or using technological solutions to advance work when needed.

Remote Work

The term "telecommuting" refers to a type of work flexibility in which an employee is authorized to perform the duties, responsibilities, and job activities at a location different from the company or job location in which he works. It is also called telecommuting.

For example, in a home construction project, the physical presence of the architect may not be required for all tasks such as the task of selecting furniture, as he can work from home and perform specific tasks.

Advantages and Disadvantages of Remote Work for Companies:

Advantages

- Reducing the financial cost since there is no need for an employee's headquarters.
- Remote workers can be more productive because they don't experience interruptions while working as they do in office work.
- Improved motivation, reduced stress levels, and reduced absences due to illness.
- An employer may be able to retain an employee by allowing them to work part-time from home when they experience certain personal circumstances.

Disadvantages

- Increased costs for the company due to the need to provide computers and means of communication to work remotely.
- It is more difficult to manage remote workers and monitor their performance.
- It carries some security risks related to the information used by the telecommuter.
- Some types of jobs are not suitable for remote work, such as a construction worker.

Advantages and Disadvantages of Remote Work for the Employee:

Advantages

- Telecommuting saves time spent each day going to work.
- Saves on the cost of using cars or public transportation to commute to and from work.
- Provides the opportunity for flexible working within the limits of professional responsibilities.
- Achieves a better balance between work and family life.

Disadvantages

- A remote worker may feel isolated as he loses social interaction with his co-workers.
- The home environment may not be suitable for working remotely effectively due to frequent disturbances in the home environment.
- The home may not have the space required to provide a suitable remote working environment.
- The home environment may lead to a lack of self-discipline to work remotely without supervision.

Examples of Home Construction Project Risks:

In the construction process, the following risks are likely to arise as illustrated in the Table 1.14:

Table 1.14: Reasons for home construction project risks

Risks		Reasons
	Financial and economic risks	• Availability of funds. • Exchange rate fluctuations. • Fiscal deficit.
	Construction related risks	• Labor disputes. • Employee productivity. • Frequent changes in design. • Equipment failure.
	Environmental risks	• Conditions for obtaining the necessary permits. • Pollution and safety rules.
	Design risks	• Incomplete design scope. • A design flaw. • Occurrence of errors and abuses. • Incomplete specification.

Exercises

1

Read the sentences and tick ✓ True or False.	True	False
1. A project is a temporary endeavor designed to achieve a specific goal or objective.	☐	☐
2. Project management involves creating a road map that outlines the various activities, milestones, and resources needed to achieve project goals within a specified time frame.	☐	☐
3. Project planning includes initiating, planning, executing, monitoring, controlling and closing the project.	☐	☐
4. A project manager is a professional responsible for leading a team and managing a project from start to finish.	☐	☐
5. Scope, time and cost are basic elements to consider before prioritizing tasks.	☐	☐
6. Deadlines and Milestones are the same thing.	☐	☐
7. Estimating project costs is a basic duty of the project manager.	☐	☐
8. The tasks of a project can be divided to subtasks.	☐	☐
9. Remote work has benefits only for the employees.	☐	☐
10. Risk management plan aims to minimize any potential problems arising from risks that may adversely affect the completion of the project.	☐	☐

2

Describe the difference between project planning and project management.



- 3 Suppose you are working on an engineering design project for building a car battery for an electric car in your country. Conduct a SWOT analysis for this project.

- 4 Explain the difference between the terms "timeline", "deadline" and "milestone".

- 5 Explain the difference between the two main methods of prioritizing tasks.



6 Explain the difference between cost management and resource management.

7 How do human resources contribute to the effective functioning of a company.

8 Explain the types of relationships between tasks in project management.

9 Briefly explain the importance of a management plan in a company.



Lesson 5

Project Management Software

Link to digital lesson



www.iien.edu.sa

Project Plan

It is an official document prepared to help monitor and implement the project. The plan is the key to a successful project and is considered the most important document to create when starting any business. The project plan is one of the most important parts of the project management process, so it must be created carefully, and the project must be broken down into smaller tasks and activities that must be performed to complete the project.

Project Management Life Cycle

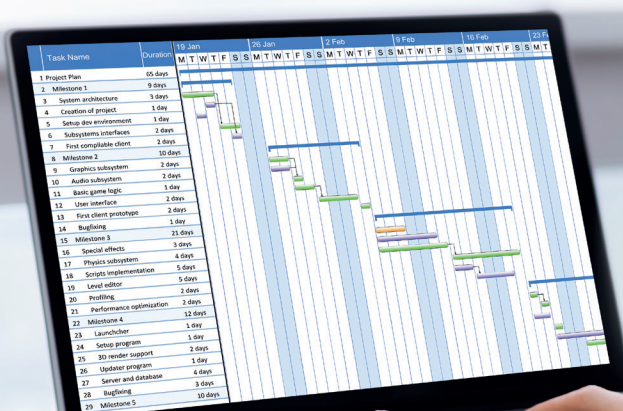
Each project goes through the following phases:

1. Conception & Initiation
2. Definition & Planning
3. Launch & Execution
4. Performance & Control
5. Project Closure

Project Management Software

The most important criterion in choosing the right project management software is the team size and the project size. There are programs designed for planning large projects and groups, such as Microsoft Project, but there are also tablet and mobile apps. Also the development approach influences the choice of software. You will use GanttProject software, commonly used in construction, media, and industries with medium-sized projects and sequential day-bound tasks.

Figure 1.22: Planning a project with Gantt charts



Gantt Chart

A Gantt chart provides a timeline that helps plan, coordinate, and track specific tasks in a project.

You will create a Gantt chart for a typical engineering design project that will follow the main stages of product development that were specified earlier in the unit. You will use GanttProject for project planning and to create a Gantt chart. The GanttProject tool can be downloaded for free from the following link: <https://www.ganttproject.biz/download/gp32>



You can change the view of the timeline to different zoom levels.

You can move through the timeline to see the start and end dates for the tasks listed in the left part of the screen

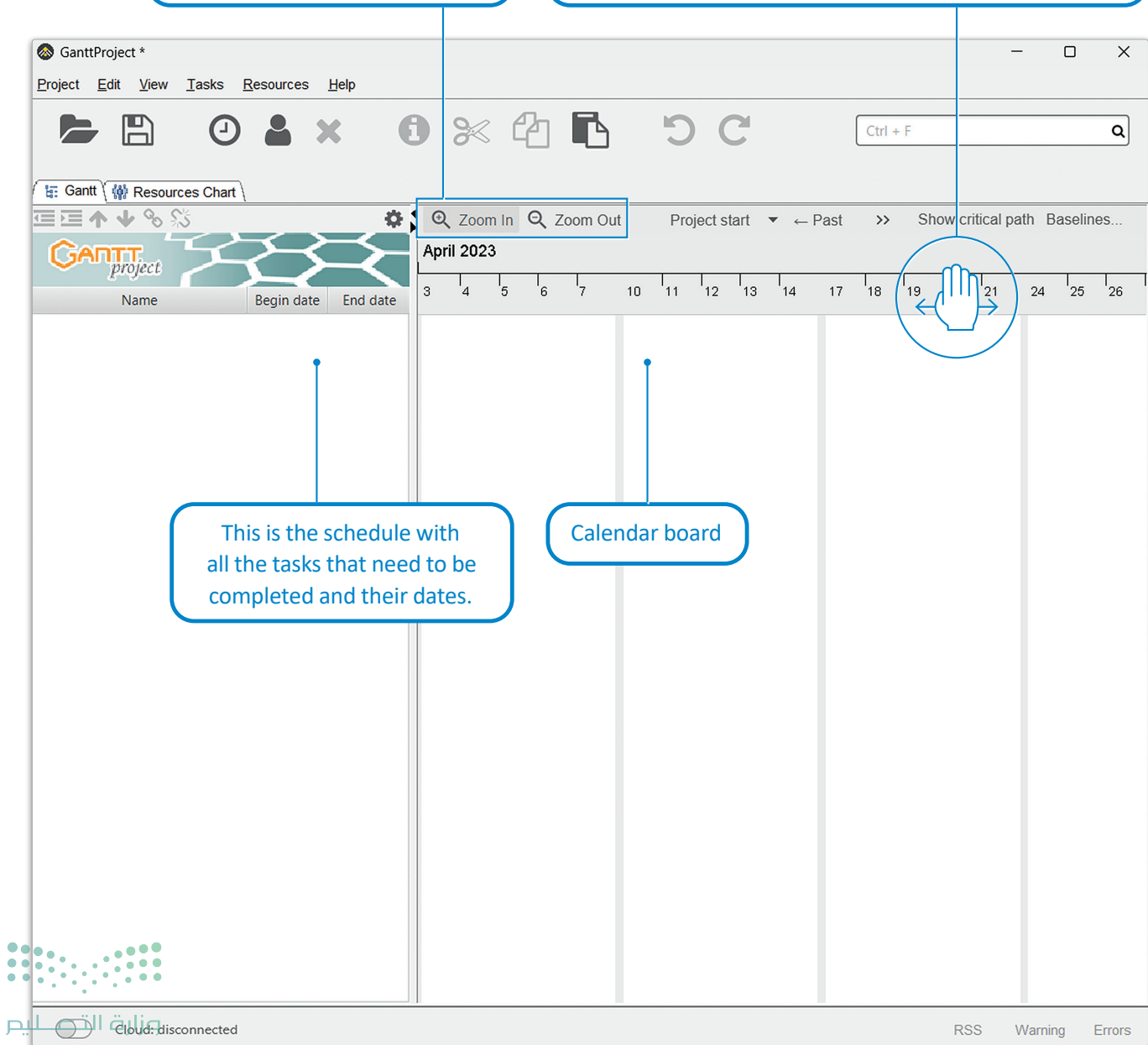


Figure 1.23: The GanttProject user interface

To create a new project:

- > Click on the **Project** menu and click on the **New** command. ①
- > Fill in the **Name** and **Organization** fields. ②
- > Click the **Next** button twice. ③
- > Set **Friday** and **Saturday** as the weekend dates. ④
- > Click **Ok**. ⑤

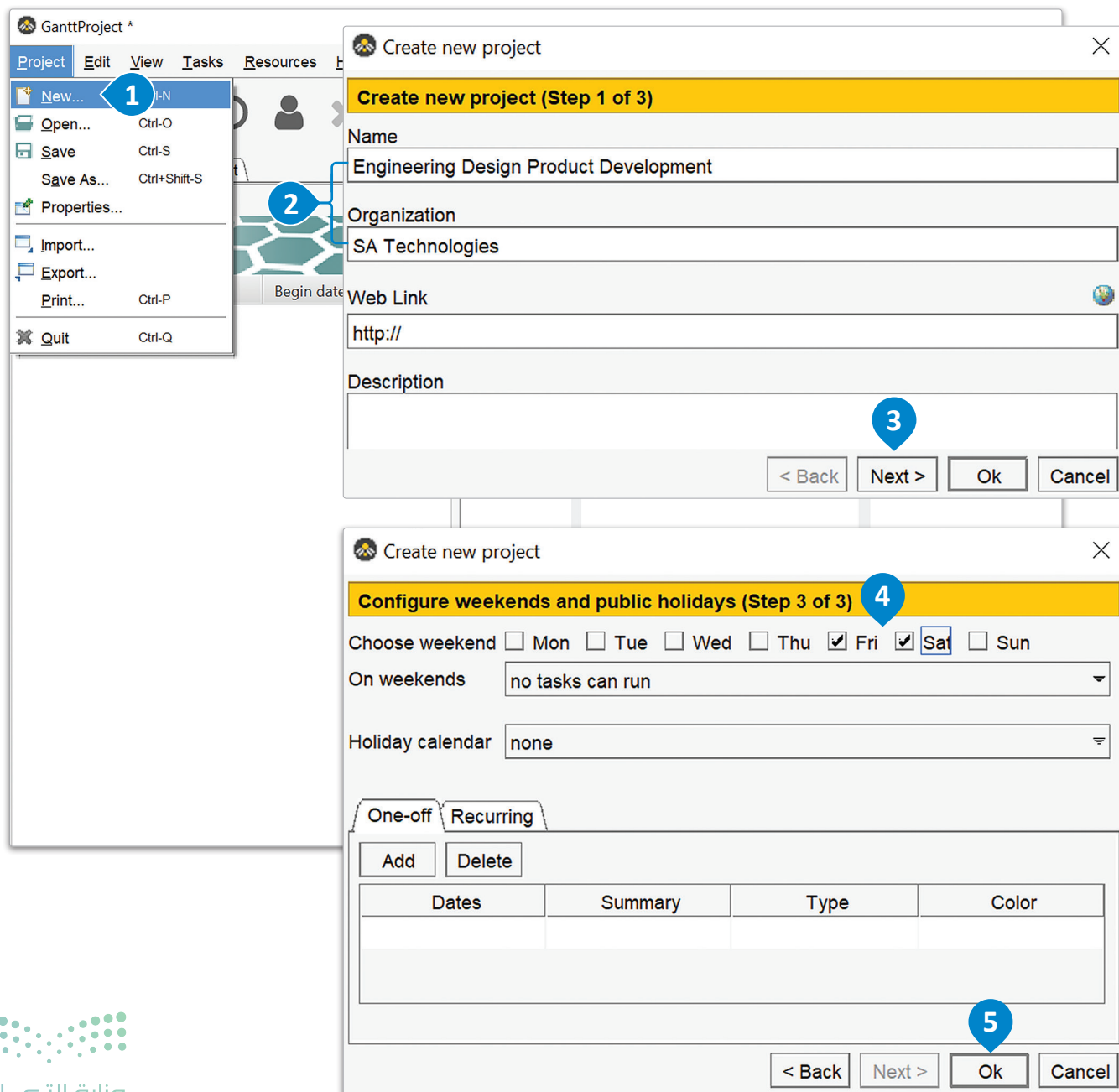


Figure 1.24: Creating a new project

To create a new task:

- > Click on the **Tasks** menu and click on the **New task** command. **1**
- > A new task with a default name is created. **2**
- > Set the name for the first task e.g., **Problem definition**. **3**

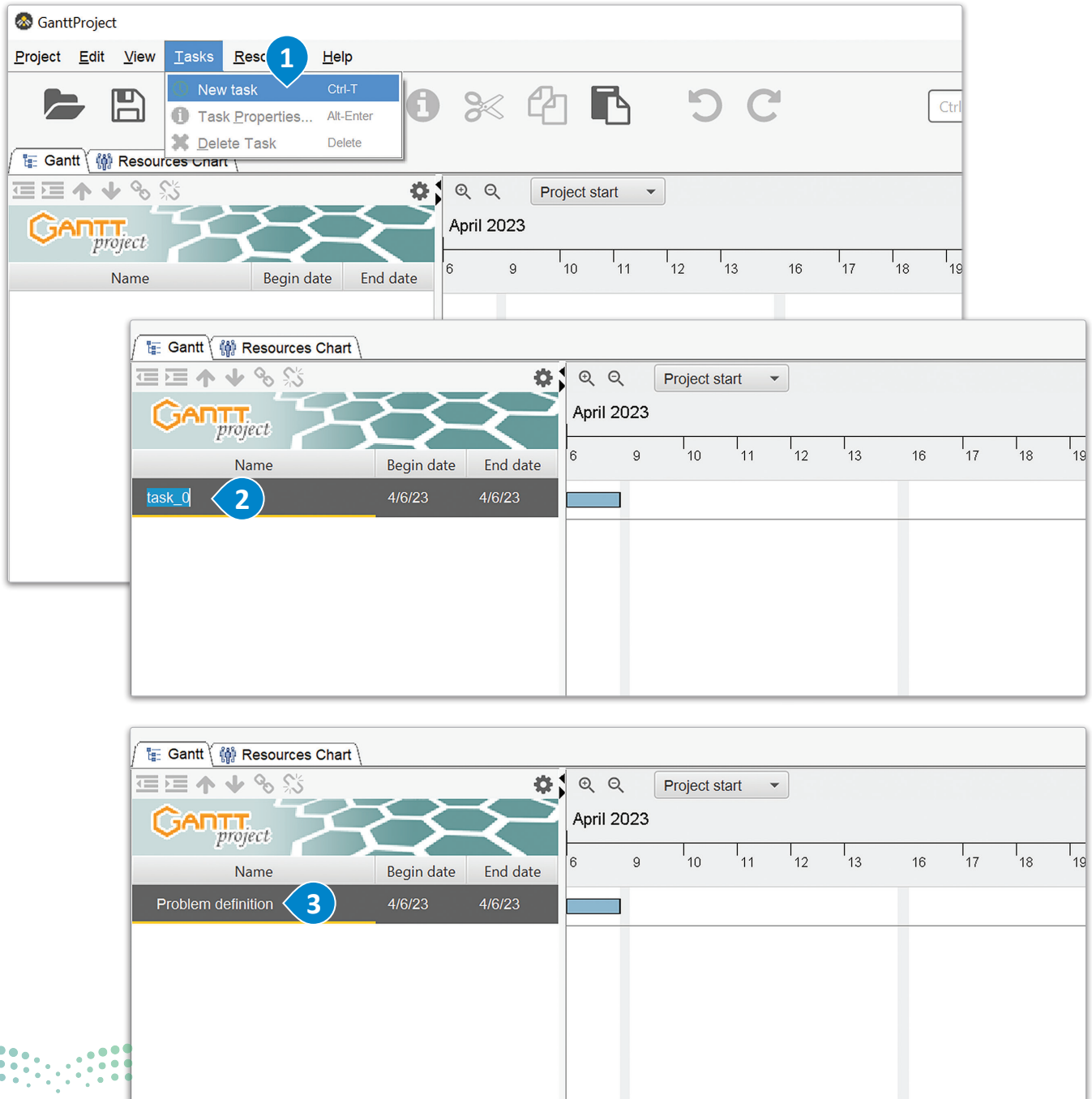


Figure 1.25: Creating a new task



To change the properties of a task:

- > In the Tasks menu, select **Task Properties** command. ①
- > Adjust the **Begin Date** by clicking on the button next to the text field. ②
- > Add a **Duration** for the task in number of workdays. ③
- > Click **Ok**. ④

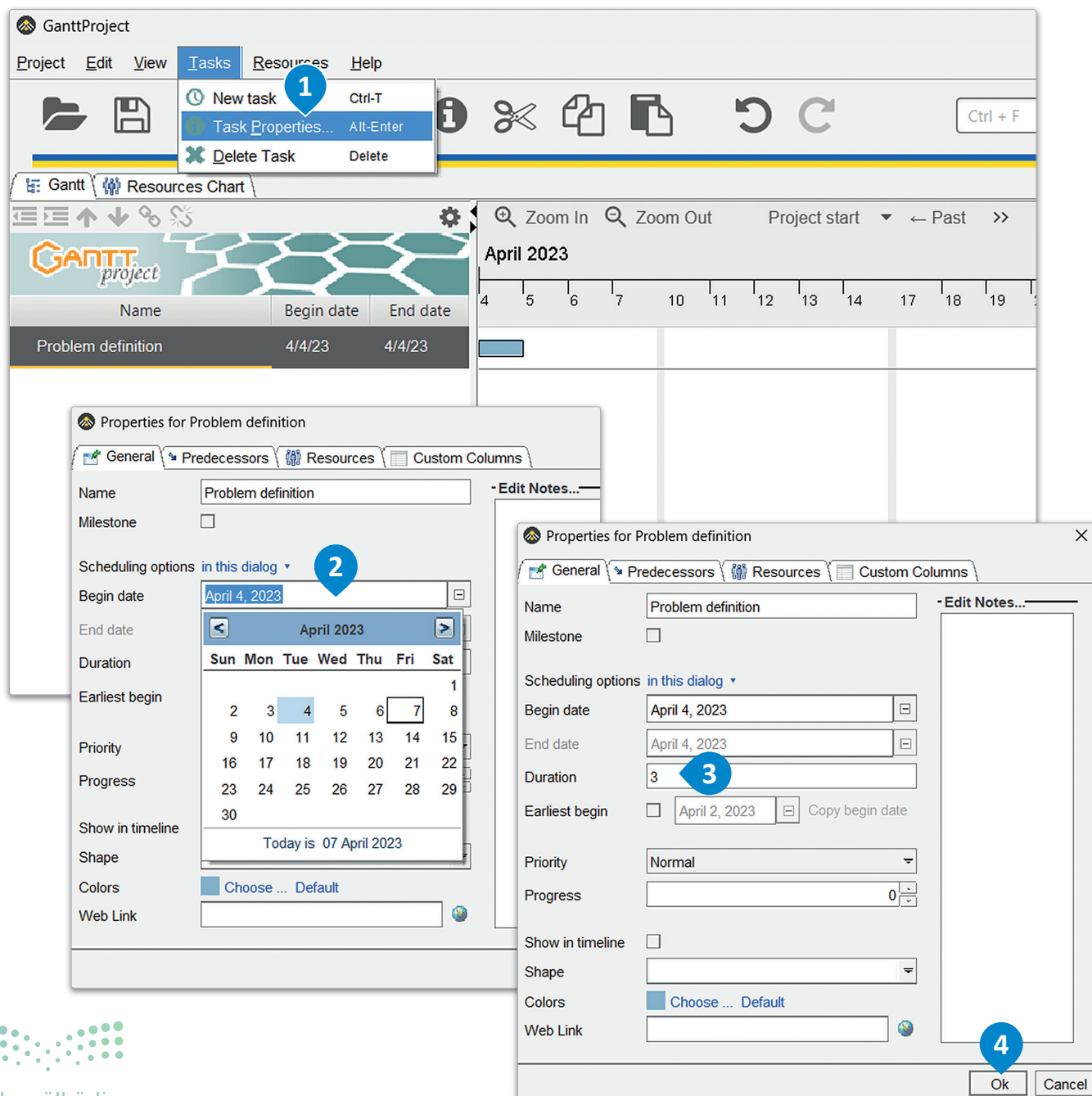
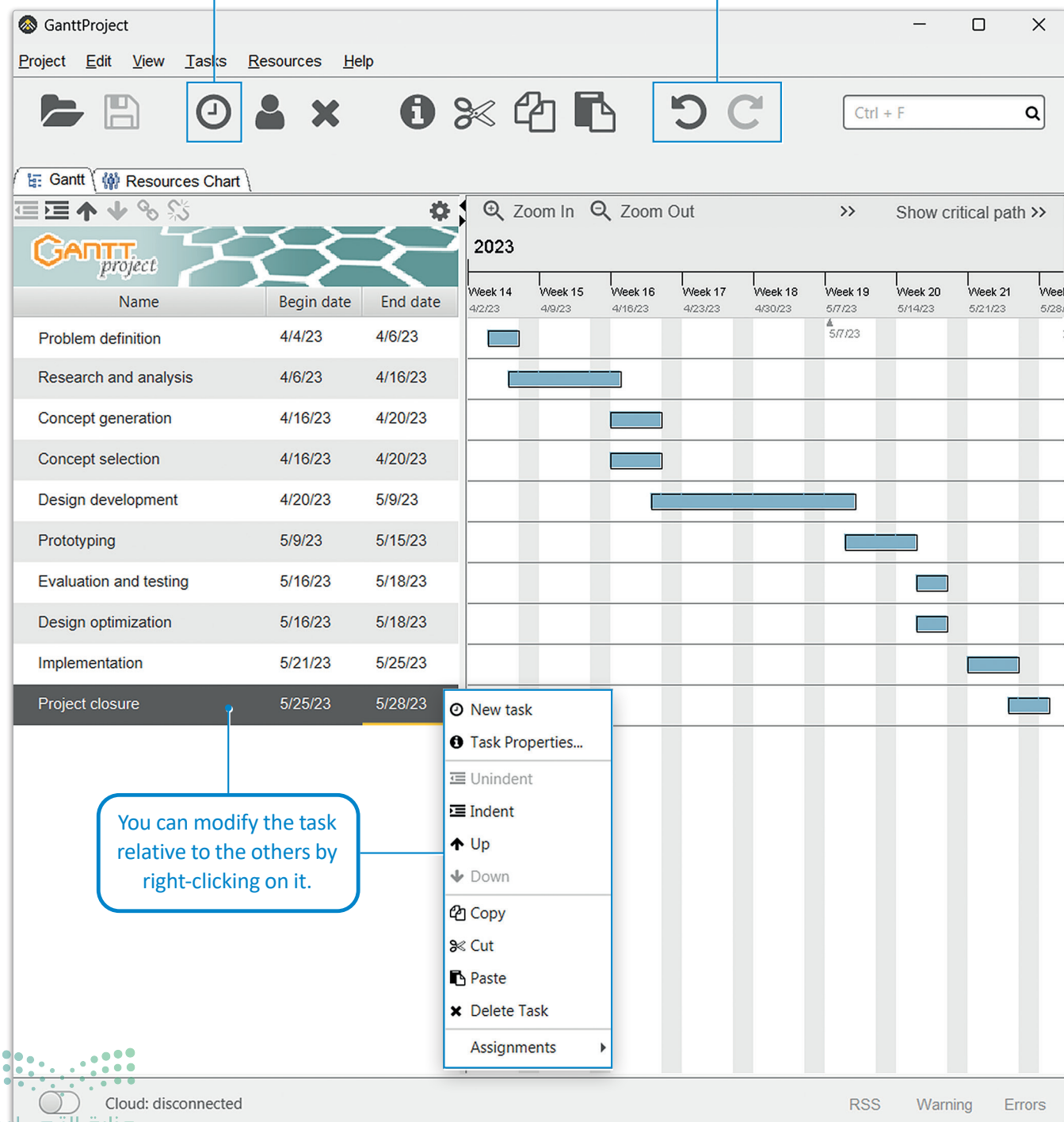


Figure 1.26: Changing the properties of a task

Fill out the rest of the chart with the following phases of the engineering design product development process and with corresponding durations. The chart will look like the following:

You can add a new task with the clock button as well.

You can undo and redo your actions here.



You can modify the task relative to the others by right-clicking on it.

Figure 1.27: Changing the sequence of tasks

A task may involve other subtasks as well. GanttProject allows you to specify tasks and their subtasks as well. In this example, you will group the concept generation and the prototyping, testing and optimizing processes in two main tasks including sub-tasks..

To create subtasks:

- > Right-click on the task you want and click on the **Indent** option to make it a subtask of the above task. ①
- > Do the same for the rest of the tasks that have subtasks. ②

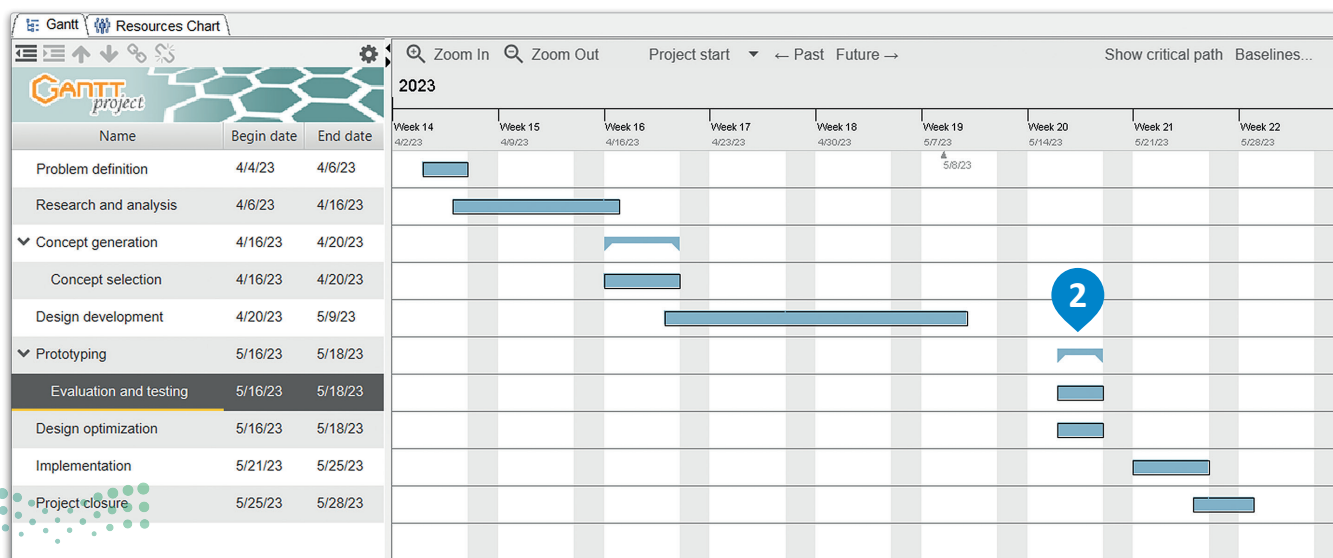
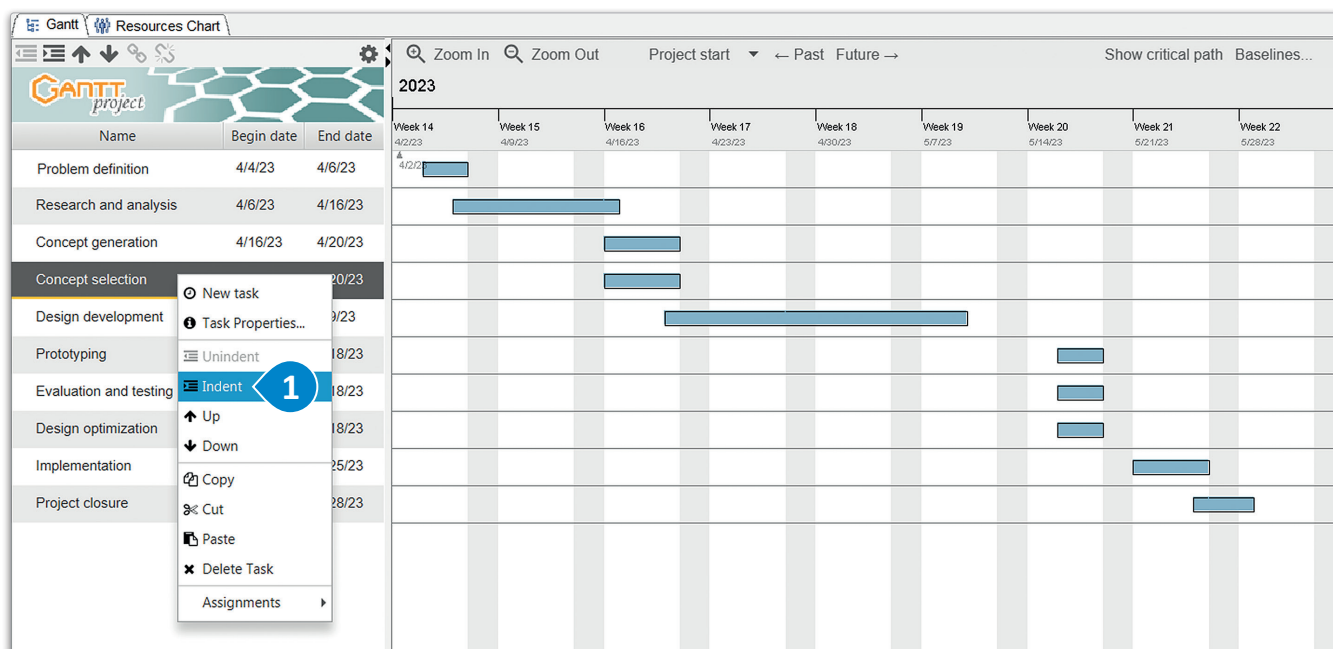


Figure 1.28: Creating subtasks

To change the priority of a task:

- > Right-click on the task you want and click on the **Task Properties** option. **1**
- > Change the priority of the task by making a selection from the **Priority** dropdown list. **2**
- > Click **Ok**. **3**

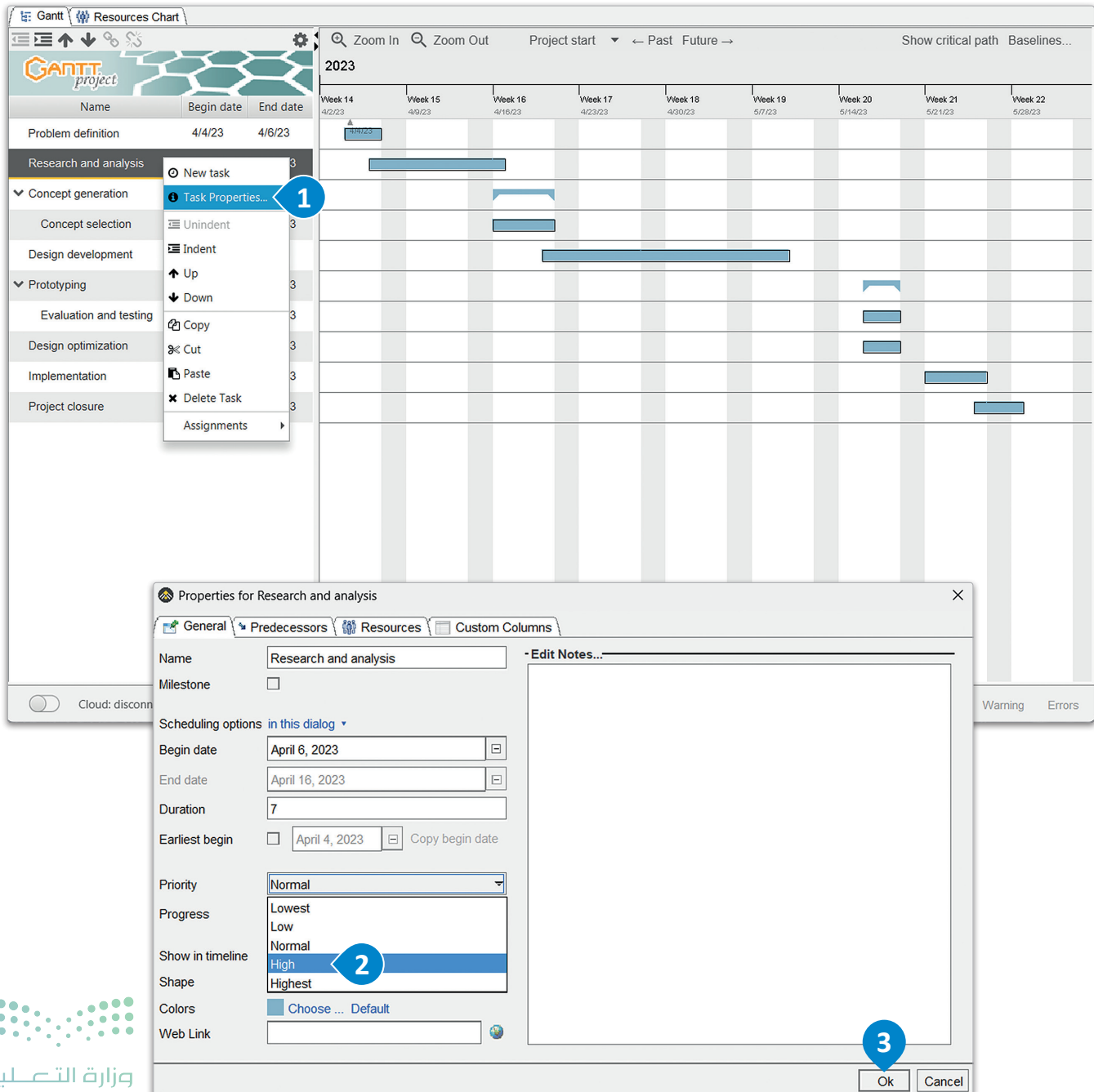


Figure 1.29: Changing the priority of a task

Now you will create milestones for the project. The points which can be considered important milestones are the selection of the design concept, the development of the design and the end implementation stages.

To create milestones:

- > Create a new task below the task that you want to be the final one before the milestone. **1**
- > In the **Properties** window set the appropriate date **2** and check the **Milestone** checkbox. **3**
- > Click **Ok**. **4**
- > Create the rest of the milestones. **5**

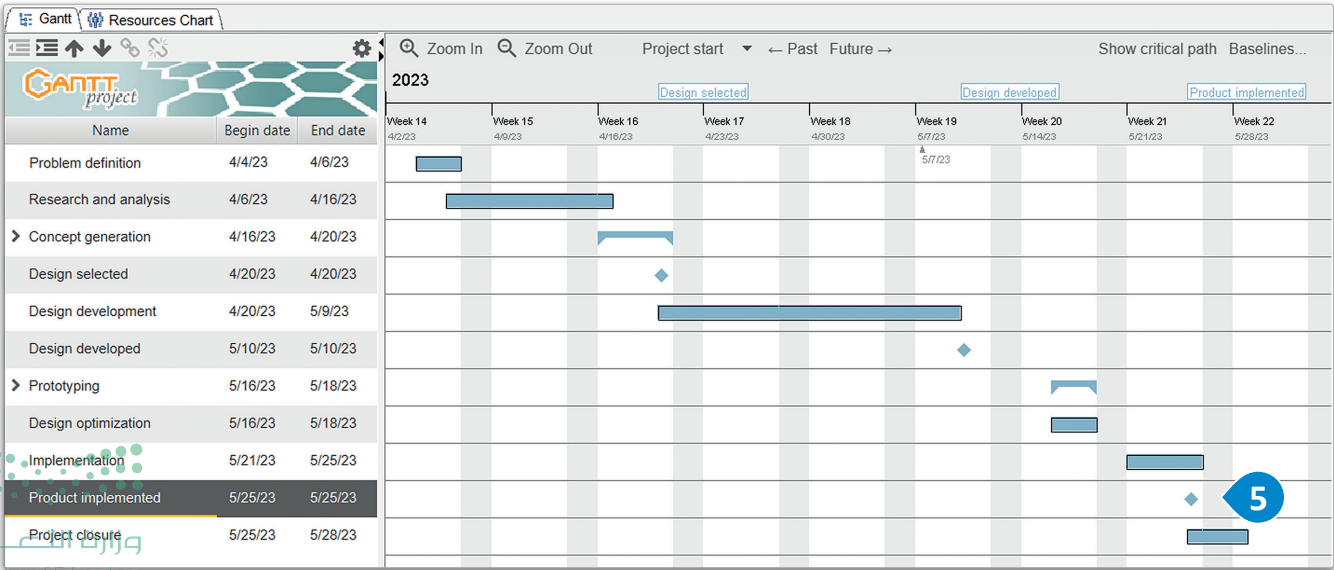
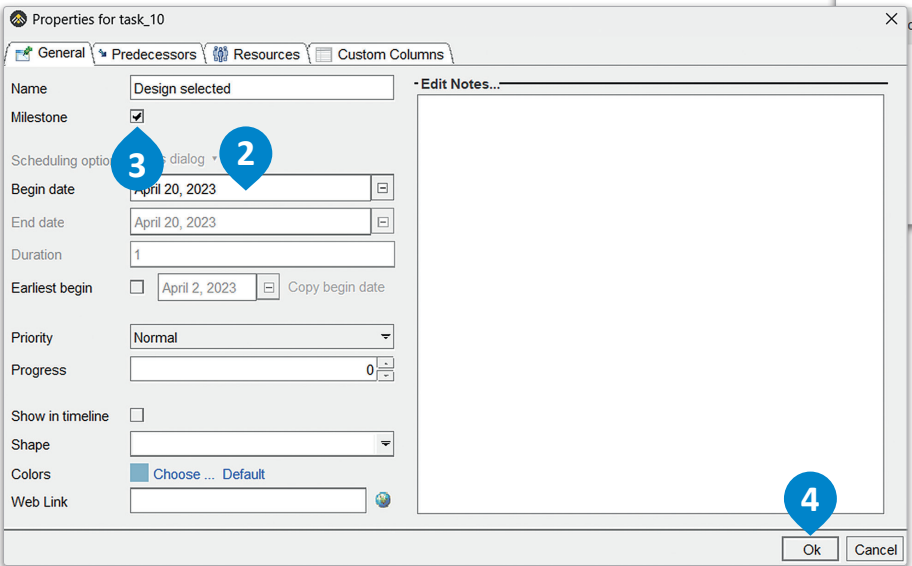
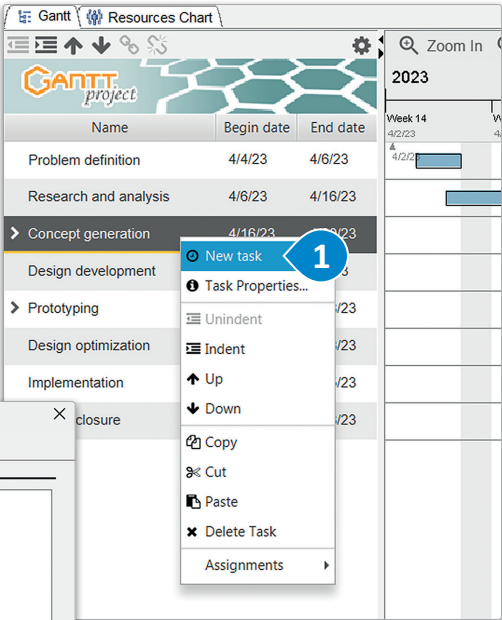


Figure 1.30: Creating milestones

In GanttProject, roles are presented in the form of resources. In order to assign a person with a role to a task, you will need to first create resource types and then create the persons with the appropriate resource type characteristic. The default job role in GanttProject is **project manager**.

To create resource roles:

> In the **Project** menu, select the **Properties** command. 1

> In the **Resource roles** tab, write the name of the role in the textbox and click the **Add** button. 2

> Add the rest of the resource roles. 3

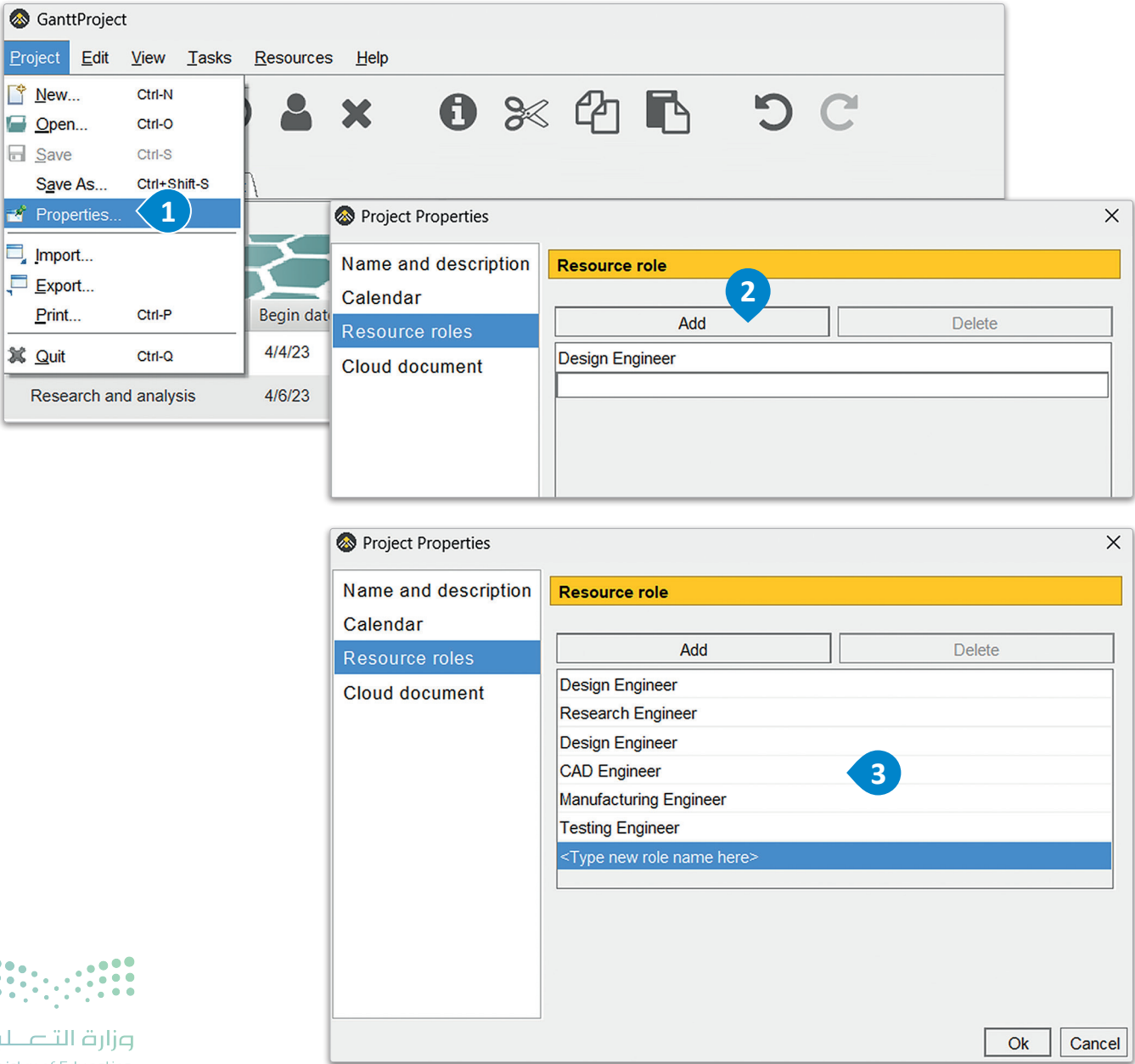


Figure 1.31: Creating resource roles

Now you will create the persons with the appropriate roles that will be assigned as resources to each task.

To create resources:

- > In the **Resources** menu, select the **New Resource** command. **1**
- > Write the **Name**. **2**
- > Add a role for the new resource. **3**
- > Click **Ok**. **4**
- > Create one person for each role. **5**

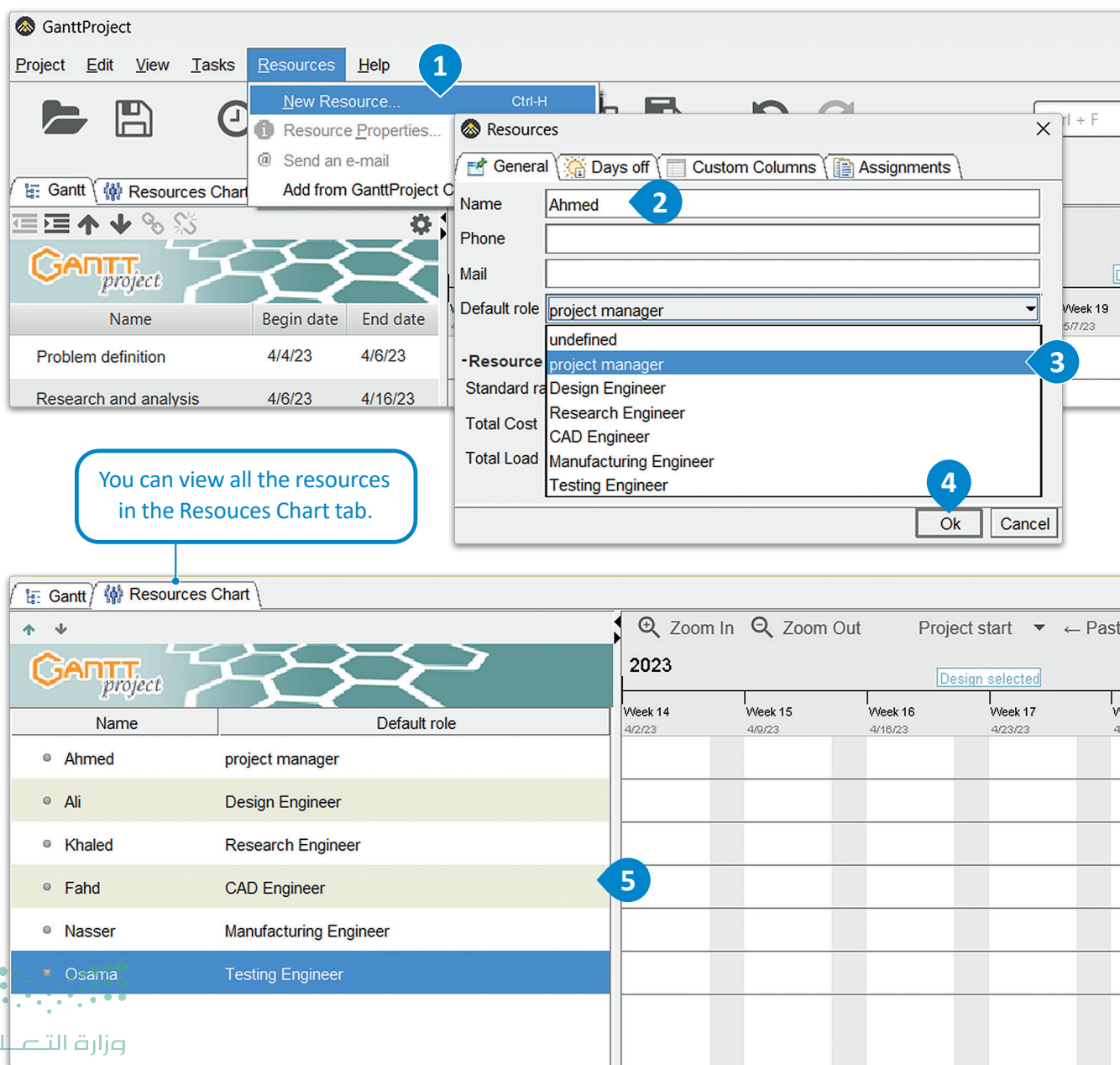


Figure 1.32: Creating resources

To assign resources to tasks:

- > In the **Properties** of a task, go to the **Resources** tab and select the **Resource Name** of the resource you want to assign to that task. 1
- > Click **Ok**. 2
- > Assign resources to the rest of the tasks. 3

The screenshot shows the 'Properties for Problem definition' dialog box in the Gantt project software. The 'Resources' tab is selected, and a dropdown menu is open, showing a list of resources: Ahmed, Ali, Khaled, Fahd, Nasser, and Osama. A blue circle with the number 1 is next to 'Ahmed'. Another blue circle with the number 2 is next to the 'Ok' button.

ID	Resource Name	Unit	Coordinator	Role
1	Ahmed	100.0	☐	

The screenshot shows the 'Resources' tab in the 'Properties for Problem definition' dialog box. A list of resources is shown with their default roles: Ahmed (project manager), Ali (Design Engineer), Khaled (Research Engineer), Fahd (CAD Engineer), Nasser (Manufacturing Engineer), and Osama (Testing Engineer). A blue circle with the number 3 is next to the list.

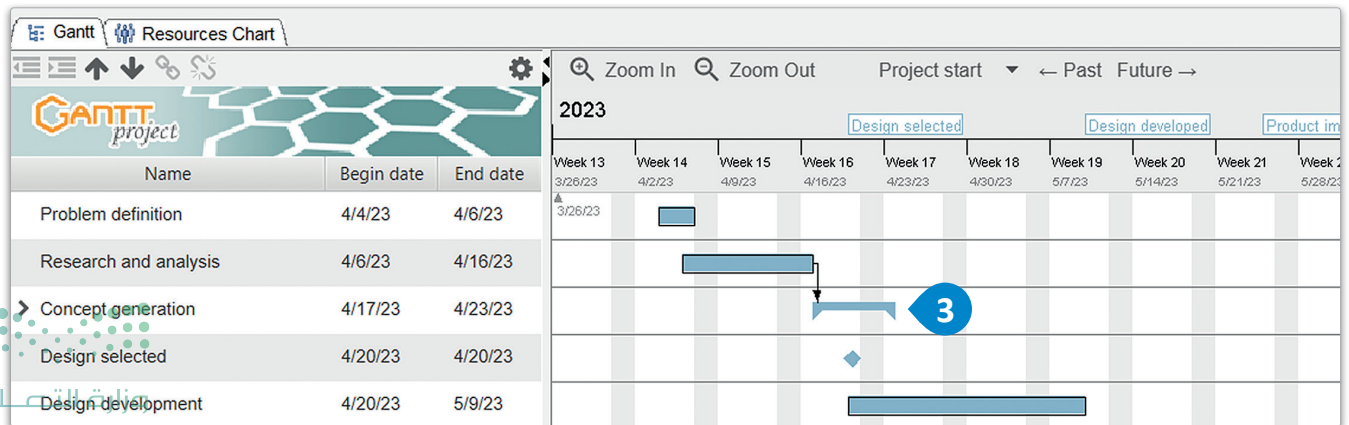
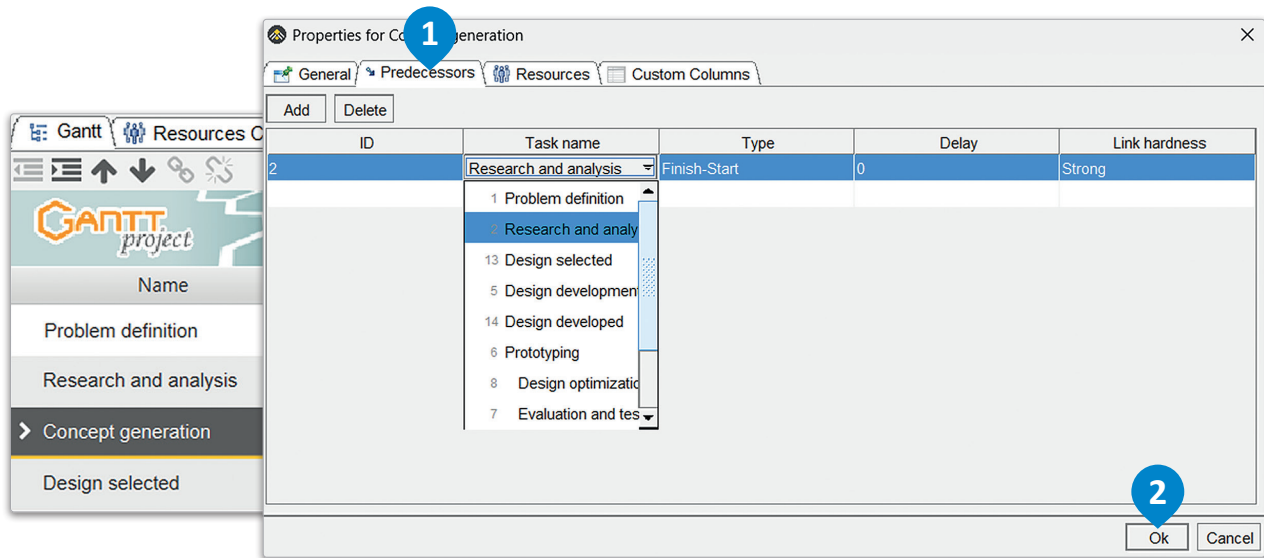
Name	Default role
Ahmed	project manager
Ali	Design Engineer
Khaled	Research Engineer
Fahd	CAD Engineer
Nasser	Manufacturing Engineer
Osama	Testing Engineer

Figure 1.33: Assigning resources to tasks

Now you will add relationships between the tasks. You will create a **Finish to Start** and a **Start to Start** relationship. The **Concept generation** task will start after the **Research and analysis** task has finished, so it will have a **Finish to Start** relationship. The **Prototyping and Implementation** tasks can start concurrently, due to the iterative nature of those tasks. For this reason, they will have a **Start to Start** relationship.

To add relationships between the tasks:

- > In the **Properties** of the **Concept generation** task, go to the **Predecessors** tab and add the Task name of the task you want to be the predecessor. **1**
- > Click **Ok**. **2**
- > The default relationship is **Finish to Start**. **3**
- > In the **Properties** of the **Implementation** task, go to the **Predecessors** tab and add the **Task name** of the task you want to be the predecessor. **4**
- > Set the Type of the relationship to be **Start to Start**. **5**
- > Click **Ok**. **6**



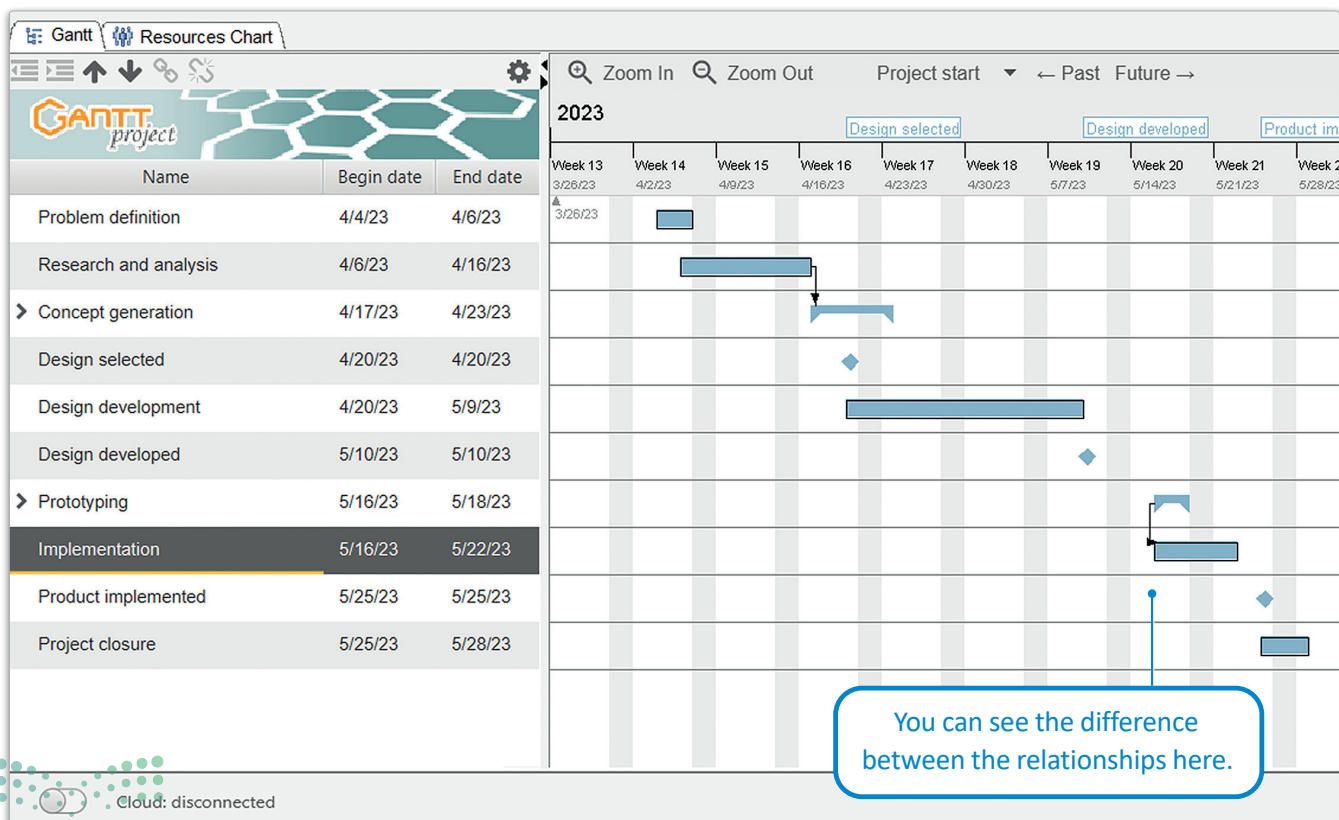
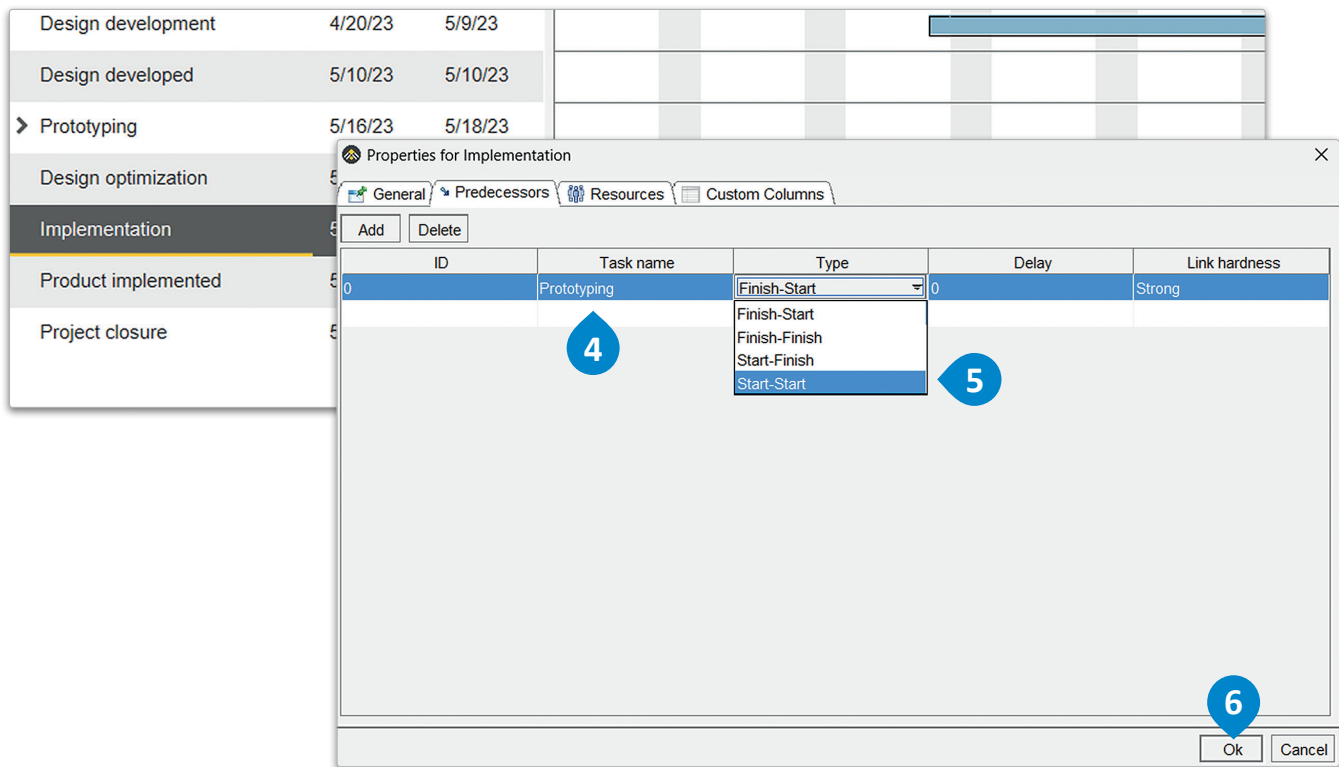


Figure 1.34: Adding relationships between the tasks

In order to see the status of all the projects, you will need to add percentages of completion to the tasks.

To add completion status to a task:

- > In the **Properties** of a task, go to the **Progress** box and set the status of the task as a percentage. **1**
- > Click **Ok**. **2**
- > The black bar represents the completion status of the task. **3**

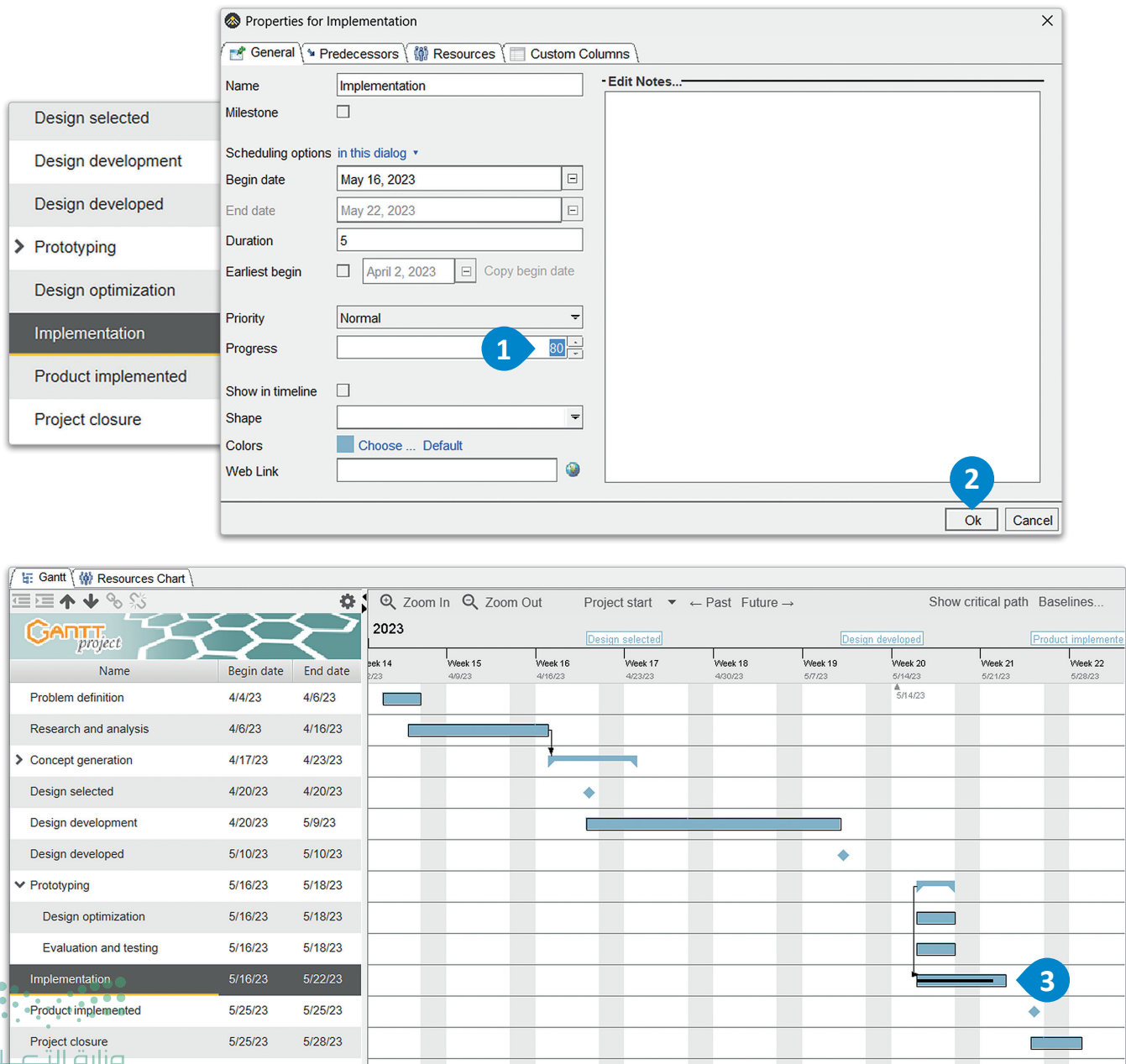


Figure 1.35: Adding completion status to a task

Schedules in a project plan are changed and iterated constantly so it is very important to save the schedule of your plan frequently.

To save your project:

- > To save your project plan schedule click on the **floppy disk icon** on the top left corner of the window. **1**
- > Fill in with a name of your choice. **2**
- > Click **Save**. **3**

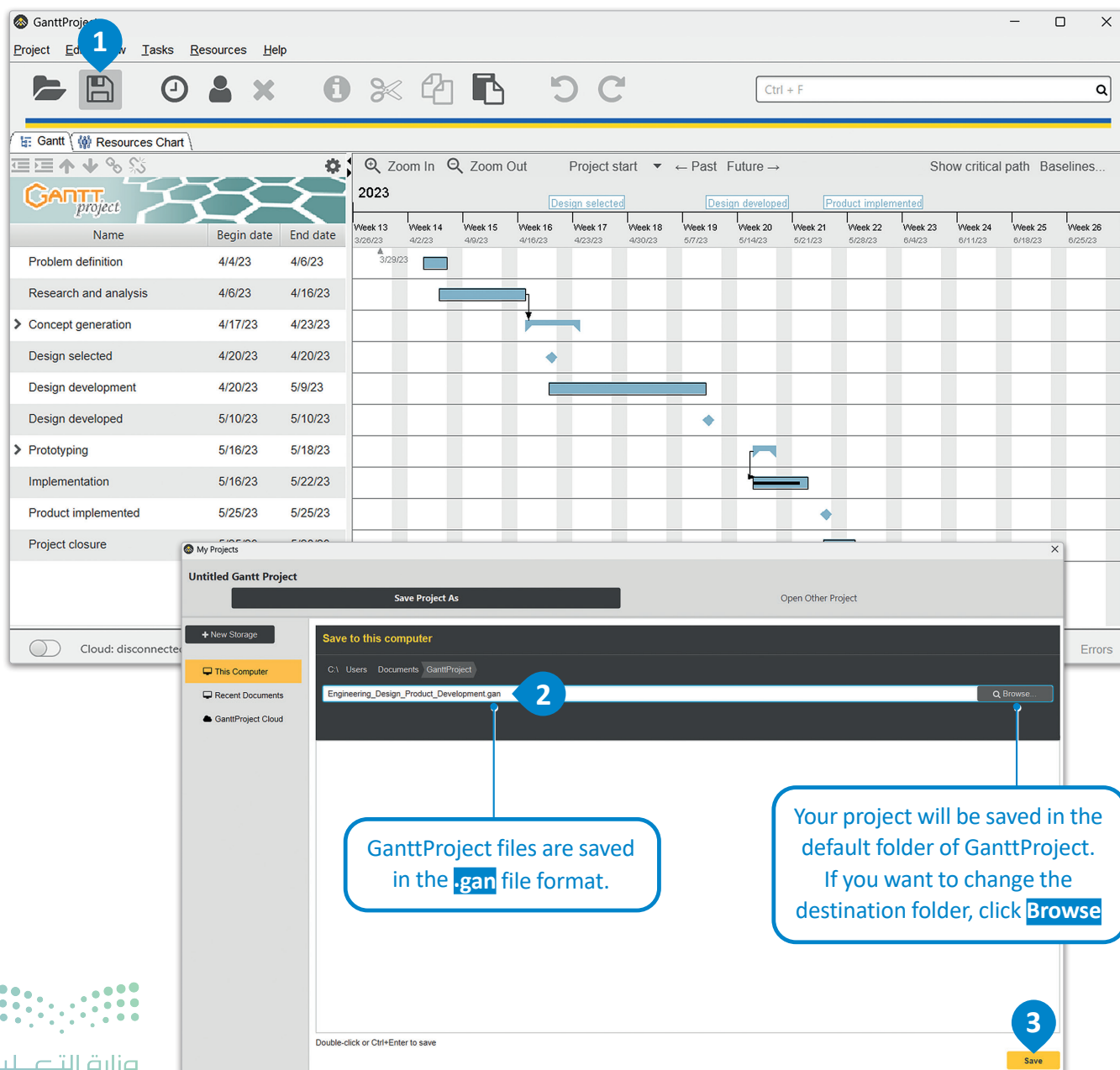


Figure 1.36: Saving your project

You can export your chart in an image format as well to share with other people on your teams.

To export your project plan as an image:

- > In the **Project** menu, select the **Export** command. **1**
- > Select the **Raster image file** option **2** and click on the **Next** button. **3**
- > In the next window set the folder you want to save your project **4** and click **OK**. **5**

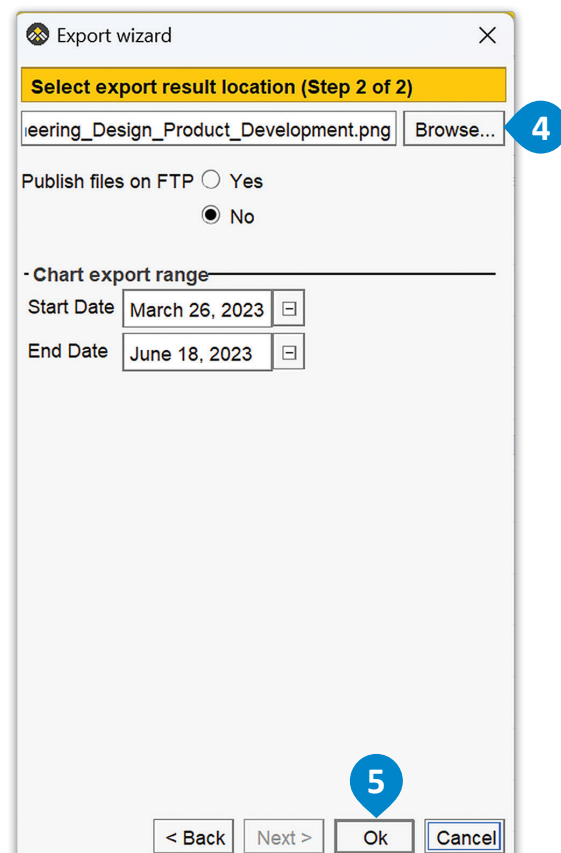
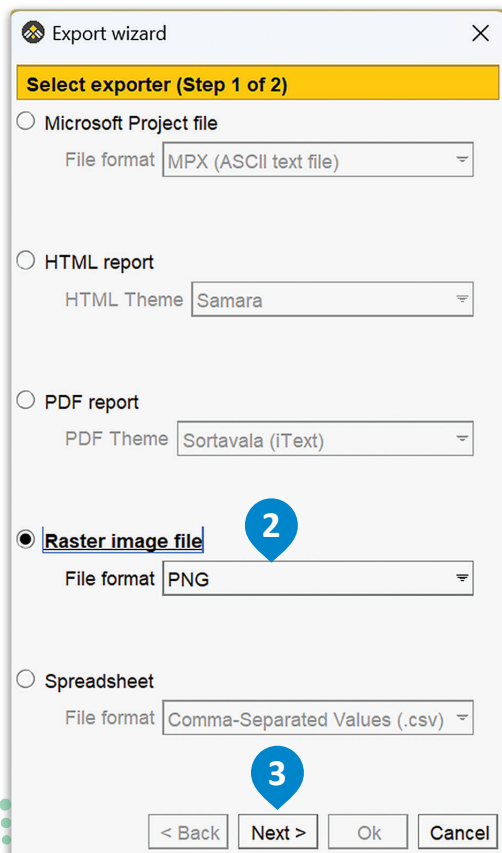
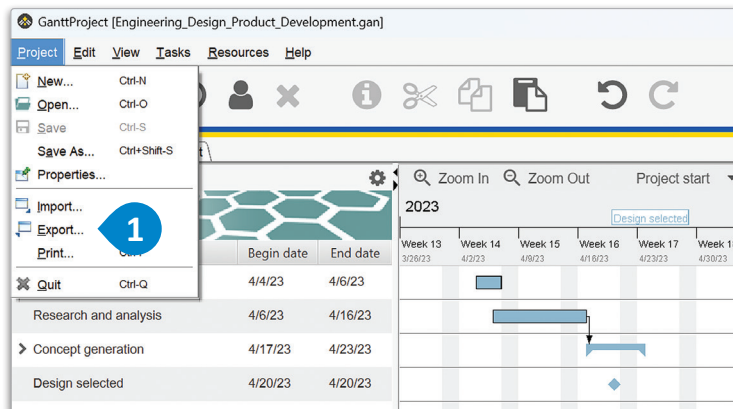


Figure 1.37: Exporting your project as an image

Exercises

- 1 Suppose you wanted the project to finish earlier than originally planned. Identify which tasks or subtasks can be shortened or to which different resources can be allocated. Update the project management plan in GanttProject to accommodate the new deadline.

- 2 Develop a plan for a school fundraiser, such as a bake sale or car wash. Create a project plan that includes tasks such as organizing volunteers, promoting the event, collecting donations, preparing food or supplies, and accounting for funds raised. Use GanttProject to allocate resources, assign tasks, and track progress.



- 3** Plan a renovation project for a room in a house. Create a project plan that includes tasks such as researching designs and materials, purchasing supplies, preparing the space, and completing the renovation. Use GanttProject to set deadlines, assign tasks, and track progress.

- 4** Plan a website design project, such as creating a personal blog. Create a project plan that includes tasks such as selecting a platform or software, designing the layout and content, coding and testing the website, and publishing the finished product. Use GanttProject to set deadlines, allocate resources, and track progress.

- 5** Plan a research project on a topic of interest, such as social media use. Create a project plan that includes tasks such as identifying sources, collecting and analyzing data, organizing findings, and presenting results. Use GanttProject to set deadlines, allocate resources, and track progress.



Project

Suppose you have been put in charge of developing the charging stations for the adoption of electric cars in a small city in the KSA. You are in charge of the development of the charging stations and then their integration into the city's power grid. The project will have a deadline of 3 years from now.

1

Create the requirements for what the charging stations should be able to do and how they must be placed inside the city itself. Think about what types of professionals will work on the development and then on the integration.

2

Write down the work tasks and subtasks that need to be completed for the development and integration of the charging stations. You will then create a project plan for the development and the integration.

3

Create a detailed schedule for all the tasks and think about which professionals will work on each task. Setup the necessary milestones for the project. Think about the relationships between the tasks and which ones need to be completed sequentially and which ones can run concurrently.

4

Use the GanttProject tool to create the project plan with all the above properties and assign the appropriate job roles to the tasks.



Wrap up

Now you have learned to:

- > Identify what engineering design is.
- > Distinguish the job roles in an engineering design project.
- > Define design thinking.
- > Analyze the various design strategies for a project.
- > Inspect measurements in engineering design projects.
- > Evaluate how materials are selected in projects.
- > Examine different types of material properties.
- > Analyze the product life cycle and its stages.
- > List product engineering processes and best practices.
- > Identify product lifecycle management processes and techniques.
- > Interpret the pyramid of production systems.
- > Provide an overview of project management.
- > Analyze the technical details of a project plan.
- > Design a detailed project plan for an engineering design product

KEY TERMS

Budget	Integration	Project Timeline
Cost Management	International System of Units (SI)	Pyramid of Production Systems
Deadlines	Product Engineering	Resource Management
Design Process	Product Life Cycle Management (PLM)	Resource Mapping
Design Strategies	Project Management	Risk Management
Design Thinking	Project Milestones	Scope
Human Resource Management	Project Planning	Stakeholders



2. Design and Prototyping

In this unit, you will understand the main process of designing and prototyping products. You will learn how to use FreeCAD to create simple 3D shapes. Moreover, you will learn how gears work and what makes them so important. Finally, you will design your first gears and learn how to define their size, placement and orientation to ensure that they work correctly.

Learning Objectives

In this unit, you will learn to:

- > Describe the main design cycle for creating a prototype.
- > Analyze how prototypes are converted from ideas to physical objects.
- > Understand the concept of design and prototyping.
- > Define the differences between 2D and 3D drawings.
- > Use FreeCAD modeling software.
- > Use workbenches in CAD software.
- > Create basic 2D and 3D shapes.
- > Understand the difference between padding and extrusion.
- > Understand the concept of constraints and their role in creating accurate and precise designs.
- > Understand the use of planes in defining the position and orientation of objects.
- > Identify different 3D views.
- > Understand the basics of gears and how they work.
- > Understand how to use multiple bodies to create a more complex 3D design.
- > Understand how to calculate the center distance between two gears.

Tools

- > FreeCAD



Lesson 1

Design and Prototyping

Link to digital lesson



www.ien.edu.sa

Design Process

To design and prototype a product, engineers and designers follow a methodology called a design cycle. A design cycle, also known as the engineering design process, is an iterative process that allows one to solve a problem and achieve an effective process for product development. A design cycle follows the following four phases, as shown in figure 2.1.

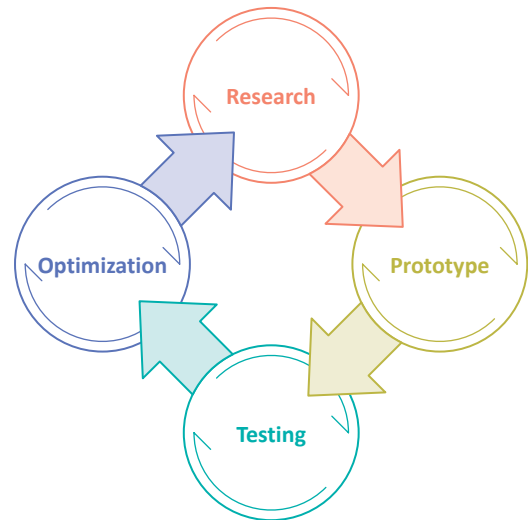


Figure 2.1: The design process

Research Phase

The first step is the research phase, which aims to define the product's purpose, the problem it solves and the users' needs. When building a product to solve a problem, the following characteristics are considered.



Figure 2.2: Armchair with aesthetic design

Aesthetics

Aesthetics defines how a product appears to the senses. Aesthetics refers to a product's shape, form, color, texture, symmetry, and proportion. Designers of consumer items seek to create aesthetically pleasing products since this can attract customers and boost sales. However, designers should not sacrifice product functionality for aesthetics. Function and form must be balanced. In engineering design, function comes before appearance, but frequently they are intertwined. Many popular designs are both functional and aesthetically pleasing.

Ergonomics

Ergonomics is the study of how humans utilize objects and interact with their environment. It considers a product's shape, size, and geometry, as well as its usability. An ergonomic product should be easy to use and comfortable, and should fit the user. Humans vary in size, so many products must be customizable to fit different consumers. For example, if an office chair is ergonomically designed, the user's posture will not cause strain or injuries. Some simple-looking objects may be ergonomically engineered. Examples include hygiene products or cutlery. These are made to fit in your hands and be easily gripped and manipulated. Complex items also require ergonomic design, like a car with many controls and a complicated user interface. When a car is well-designed, all controls are conveniently accessible to the driver.



Figure 2.3: Office chair with ergonomic design

Anthropometrics

Anthropometrics measures human proportions and physiological metrics. Anthropometric measurements are obtained from people of different ages, genders, and sizes and compiled into tables and diagrams so designers can verify that products fit the end user. Designers must examine the product's target audience and build it accordingly. For example, seats on a car may be used by persons in various percentile ranges, so designers must make them suitable for all. Anthropometric measurements of users will be included in the design specification.



Figure 2.4: 2D and 3D posture analyses



Figure 2.5: Product safety according user needs

Safety

New product development must prioritize product safety. Designers must guarantee that products are safe for consumers and the environment. If a product causes harm, the business faces legal action, fines, and brand damage. Product safety must be considered while deciding on numerous criteria, such as ensuring the material is not toxic or harmful or adding safety measures to avoid injury. When assessing user needs, consider how the user will use the product and whether parts could be hazardous. Most consumer items need human involvement.

Prototype Phase

The main stages in the prototyping phase typically include the following:

Prototype design: Based on the ideas generated during the earlier stages of the design cycle, designers create a preliminary prototype design, outlining the key features and specifications.

Material selection: Selecting suitable materials for the prototype is essential for accurately representing the final product. Designers may choose from various materials, including foam, plastics, metals, and wood.

Prototype construction: Using the design and selected materials, the prototype is constructed either by hand, additive manufacturing techniques (rapid prototyping, for example, 3D printing), or subtractive manufacturing techniques (For example: Computer Numerical Control (CNC) machines, milling, drilling, and laser cutting machines). The prototype should be built to a high level of accuracy to ensure it accurately reflects the final product.

Refinement: The prototype is refined and improved based on the client's feedback. This may involve making design changes, selecting different materials, or making other modifications to ensure the prototype accurately reflects the final product.

Repeating the process: Depending on the design's complexity and the client's continual feedback, the prototyping phase may need to be repeated several times until the final product design is achieved. Each iteration should bring the design closer to the desired outcome and help to ensure that the final product meets user needs and expectations.



Figure 2.6: Assembly drawing of a device in a 3D CAD software

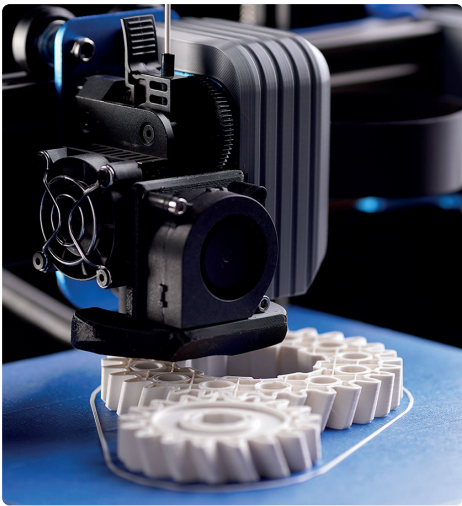


Figure 2.7: 3D printing of a prototype

Physical prototypes

Physical prototypes are essential for many reasons. A physical prototype may be created so the client or user can review the product's aesthetics before production begins. In other cases, the product may be made of multiple components, so physical prototypes are needed to ensure proper assembly and interoperability. Before final production, human-interfaced products almost always need prototypes. Sometimes a physical prototype is made so a person can use it and give feedback to the designer. The designer can modify the shape of certain features or the weight to make it more ergonomic. Some prototypes may need to be exact replicas of the final product because they may need to be produced from the same material as the final product. This allows them to be tested under real-world conditions later in the design cycle, so the designer knows the product is safe to sell. There are various methods to manufacture physical prototypes. The most popular include CNC machining and additive manufacturing with 3D printing.

Testing Phase

During the testing phase, there should be rigorous and standardized procedures to fix problems in a potential design or prototype before the manufacturing phase. It is preferable to devote time and resources to testing in the early stages of product development to avoid fixing and repair costs in a later development phase. There are various types of testing during the design and prototyping of a product, including:

Usability testing

It is necessary to test if the first designs and prototypes fit the market's needs. The designer or company may share prototypes or final renders with a sample of users to get feedback. Focus groups may test the product and provide comments. The designer can then make small changes before production. Companies can employ market testing techniques such as focus groups, questionnaires, and interviews to measure interest in a new product and learn about its target market or group. They can compare this to past market research to ensure the product fits user needs.

Performance testing

Physical testing improves product performance. Various users develop and test multiple variations to improve function or ergonomics. Real-world testing is sometimes needed. Physical tests push a prototype to its limits to ensure it can survive the forces and stresses of operation. This testing destroys the prototype. When a new car design is released, many prototypes are developed and destroyed in simulated wrecks and accidents. These expensive prototypes are needed to validate the design's safety before it can be sold. Because their failure could endanger lives, designers must ensure that components and products work under harsh conditions. Non-Destructive Testing (NDT) tests the integrity of components, such as welds.

Final Render

Photorealistic simulations of computer-generated models that give an overview of how a completed product appears without the need to manufacture a physical copy.

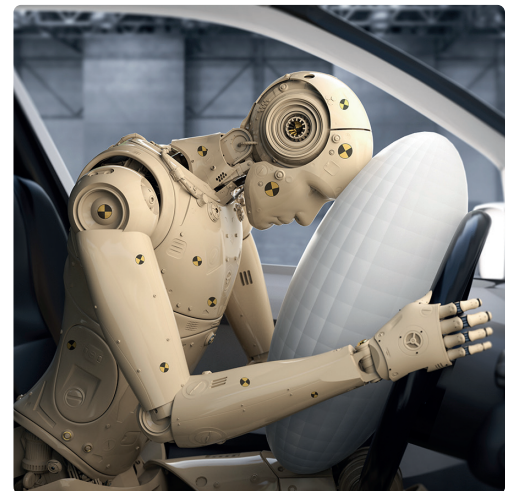


Figure 2.8: Crash test with 3D rendering dummy

Non-Destructive Testing (NDT)

Non-Destructive Testing is where products are tested close to their physical limits without reaching breaking points or causing damage.

With modern CAD and simulation tools, it is now possible to execute accurate virtual tests. Virtual prototypes can cut development time and cost but seldom replace actual prototypes. Virtual tests explain how mechanisms work by animating component assemblies and simulating tests with Finite Element Analysis (FEA) mainly for stress and strain analyses and Computational Fluid Dynamics (CFD) for fluid analysis.

They can also be used to simulate manufacturing processes. Simulations can depict how liquid metal flows in a casting process or how plastic flows in an injection-mould tool. This helps designers ensure error-free production.

Figure 2.9 and Figure 2.10 shows examples of FEA and CFD methods.

Finite Element Analysis (FEA)

Software simulations that test how elements and components react to different applications of external forces and stresses.

Computational Fluid Dynamics (CFD)

Software simulations that test how liquids and gases interact with different components and elements in a product.

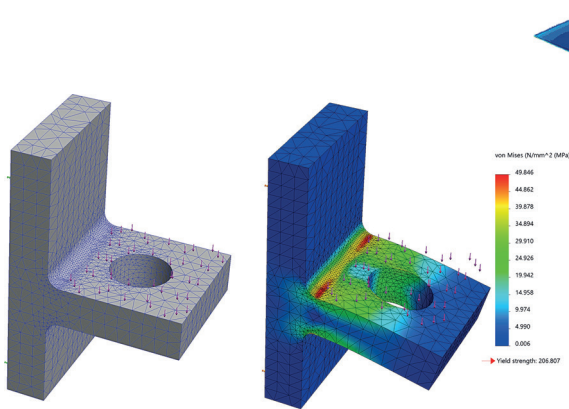


Figure 2.9: Finite Element Analysis (FEA) result of a solid model

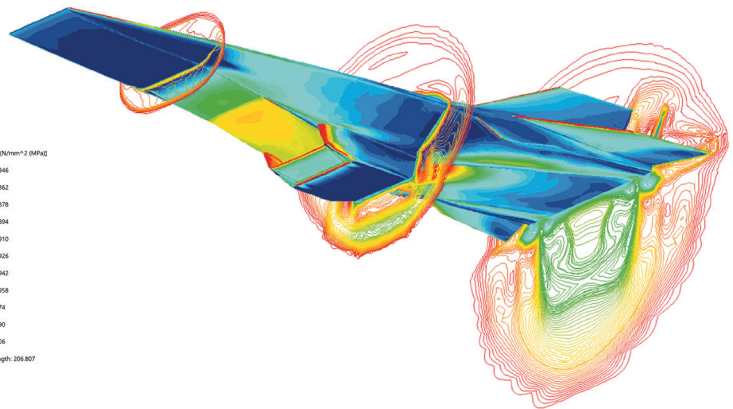


Figure 2.10: Computational fluid dynamic (CFD) image of the NASA Hyper-X at the Mach 7 test condition with the engine operating

Optimization Phase

In the optimization phase of the design cycle, the proposed design is improved to be the best possible solution. To do this, designers create a component or product prototype. Then they test it and make improvements in the design. The process of creating a prototype, testing it, and modifying the design is repeated. Product iterations improve design and prototype plans.

In some cases, this may involve hundreds of prototypes and design changes, with gradual, measurable improvements each time. Optimization can improve manufacturability, performance, or ergonomics. For example, an F1 car's rear wing goes through multiple iterations to improve aerodynamics. Designers will make multiple wing prototypes to test different designs. They will make minor design changes, create new prototypes, and test until they have the best design. Design optimization requires compromises because product development projects often have limited time, money, and resources. In cases where only minimal product safety compromises can be made, optimization phase is critical to reducing product development delays.

Another part of the optimization phase is the improvement of the manufacturing processes and the use of new materials. Additive manufacturing and smart automation can change a design's performance.



Figure 2.11: Prototype inside aerodynamic tunnel

Additive manufacturing

Additive manufacturing is a process of making three dimensional solid objects through adding material layer by layer. Additive manufacturing can remove many of the geometry limitations of traditional manufacturing methods. Design instructions may be simplified to allow the prototype to be manufactured more efficiently by smart automated machines. If the product is mass-produced, the designer may also optimize its assembly.

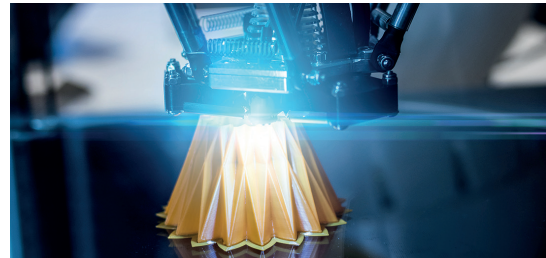


Figure 2.12: Additive manufacturing process

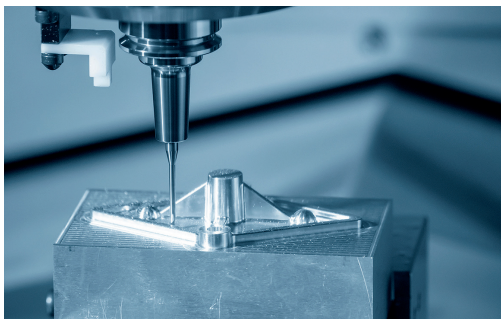


Figure 2.13: Subtractive manufacturing process

Subtractive manufacturing

Subtractive manufacturing is a process of creating three-dimensional objects by removing material from a larger block or piece of material. This is done by using a variety of cutting tools such as saws, drills, lathes, milling machines, and other specialized tools that are used to remove unwanted material to shape the final product. The process typically starts with a block of raw material that is larger than the final product, and the material is gradually removed until the desired shape is achieved.

Smart automated production

Smart automated production requires a large investment in equipment, so designers must consider how it will affect the final selling price. Also, designers are always considering the most advanced materials that can be used to improve their products. One example is the manufacturing of trucks. Trucks are traditionally powered by liquid fuel, but the move to electric engines means installing heavy lithium-ion batteries. Truck manufacturers are therefore beginning to use composite materials, such as carbon fibre components, to mitigate the increased weight of electric batteries.

Prototyping

Traditional engineering drawings were hand-drawn with pens, pencils, rules, squares, protractor and caliper on a drawing board and large sheets of paper. Most are now created on a computer. CAD software is the most popular way to create 2D and 3D engineering drawings. The designer or engineer usually creates the drawing in 3D, then presents and enhances it in 2D to convey enough detail for manufacturing.

3D Drawing Techniques

The main techniques used in 3D CAD drawing are pictorial drawings. Pictorial drawings are 3D representations of an object that are observed through specific viewpoints. There are four main types of pictorial drawings:

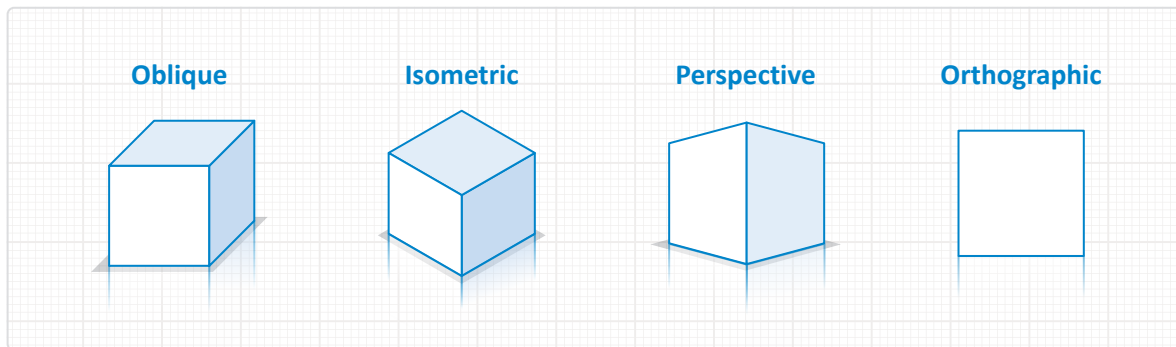


Figure 2.14: 3D drawing techniques

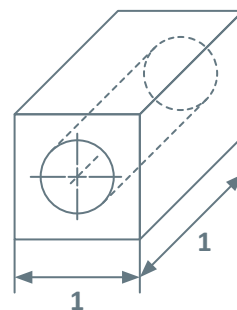


Oblique drawing

In oblique drawing, the 3D model focuses on the face of the model, which is presented with an angle of 45 degrees to the X-axis. There are two types of oblique drawing, which differ with respect to the object's proportions in the viewpoint. These are the cavalier view and cabinet view.

In a cavalier view, all the proportions and sides of the object are presented in their full size. In a cabinet view, the front face is presented in the full size, but the other proportions are half size.

Cavalier view



Cabinet view

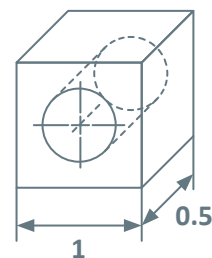


Figure 2.15: Oblique drawing examples



Isometric drawing

In isometric drawing, the 3D model focuses on the side of the object, which is presented with an angle of 30 degrees to the X-axis. In contrast to oblique cabinet view, the original proportions of the object are viewed.

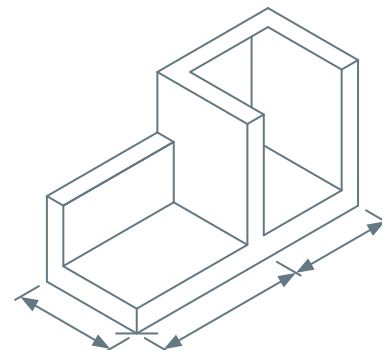


Figure 2.16: Isometric drawing example

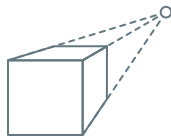




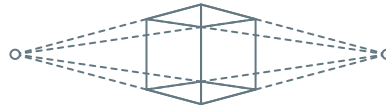
Perspective Projection

In perspective projection, the 3D model is presented in a way that simulates spatial depth. There are three types of perspective drawings:

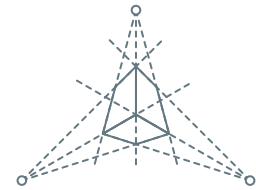
- One-point perspective: Displaying three-dimensional objects on a two-dimensional surface using intersecting vertical and horizontal lines. These lines begin from a single point on the surface which is called a vanishing point. A vanishing point is a point in a perspective drawing where parallel lines appear to converge and meet at a single point on the horizon.
- Two-point perspective: The horizontal lines begin from two points in the surface.
- Three-point perspective: The horizontal lines begin from three points in the surface.



One-point perspective



Two-point perspective



Three-point perspective

Figure 2.17: Perspective projection examples



Orthographic Projection

Orthographic projections provide 2D views of the product mainly from three sides, Front, Side, Top views. They provide the detailed information necessary for the manufacture of the product, including specific measurements for each component and how it is joined to other components. Orthographic drawings are made to scale.

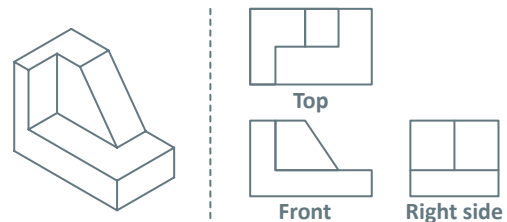


Figure 2.18: Orthographic projection examples

In addition to these techniques, assembly drawings, including exploded views, are often made to provide useful representations of the relationships between components and the order of their assembly.

Assembly drawings

An assembly drawing represents how a product with multiple joined components will be assembled to produce a final product. These drawings are produced in 3D CAD applications and allow manufacturers or clients to view the model before assembly.

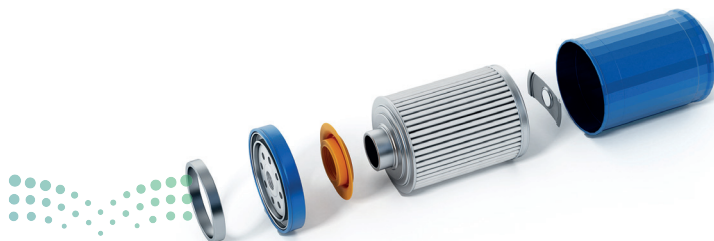


Figure 2.19: Exploded view of an oil filter assembly

Bill of Materials (BOM)

A Bill of Materials (BOM) is a comprehensive list of all the materials, components, and subassemblies needed to manufacture a finished product.

Item	Quantity	Cost per unit	Total cost
Wood Board	1 piece	15	15
Wood Glue	1 bottle	5	5
Screws	8 pieces	0.25	2
Sandpaper	1 set	5	5
Wood Stain	1 can	10	10
Total cost			37

Figure 2.20: Sample bill of materials for a wooden stool

Exploded views

Exploded views are assembly drawings that show separately each part, its relationship with other parts, and how the product is assembled. Each part is usually numbered with an index to a parts list. Although assembly drawings and exploded views are used to understand a product, they do not provide the necessary information for the manufacturing machines to produce the parts. 2D drawings are required to provide specific details about the proportions of the components that need to be manufactured.



Figure 2.21: Exploded view of a car assembly

Prototype Rendering and Manufacturing

After a 3D model is produced, it needs to be rendered. The materials, proportions, and results from the physics simulations during the rendering stage are applied to create a photorealistic virtual prototype. This is used to show the prototype to stakeholders and manufacturers. In the rendering stage, further revisions may occur before the prototype's manufacturing, saving time and physical resources.

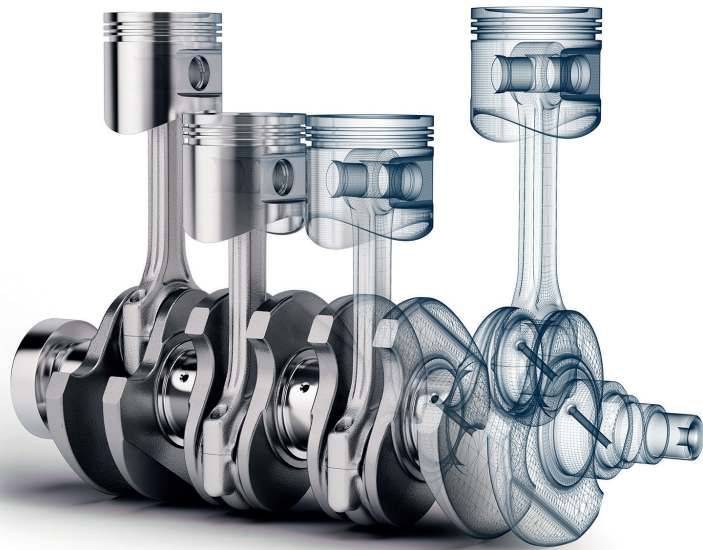
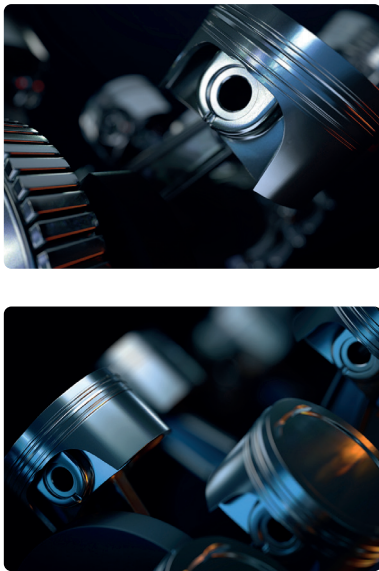


Figure 2.22: Rendering variations of model prototype

The final step is to manufacture the prototype. This can be done with cheap manufacturing techniques like basic 3D printers, or additive manufacturing or CNC manufacturing may be used for more realistic prototypes. A physical prototype will give the most accurate representation of the product so that the iterative design cycle can continue.

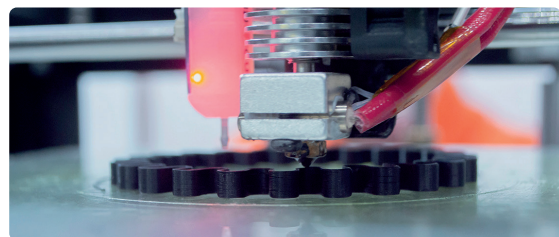


Figure 2.23: 3D printing a prototype in a 3D printer

Exercises

1

Read the sentences and tick ✓ True or False.	True	False
1. 3D models can only be created with CAD tools.	☐	☐
2. Composite materials are not used in the optimization phase of the design cycle.	☐	☐
3. CFD simulations are a part of the virtual testing of a prototype.	☐	☐
4. Isometric drawings are used to produce 2D models.	☐	☐
5. Cabinet views do not present the original proportions of a 3D model.	☐	☐
6. Exploded views are not a type of assembly drawing.	☐	☐
7. 2D technical/engineering drawings with assembly information are used to manufacture components.	☐	☐
8. Perspective drawing utilizes only horizontal lines to create 3D models.	☐	☐
9. The term rendering only applies to the material production of the prototype.	☐	☐
10. CNC manufacturing cannot be used for building prototypes.	☐	☐

2

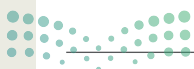
Classify the main types of research during the research phase of the design cycle.



3 Analyze the difference between physical and virtual product testing during the testing phase of the design cycle.

4 Describe how a designer works alongside manufacturers in the prototype phase of the design cycle.

5 State how iterative design processes are used in the design cycle's optimization phase.



6 Describe how CFD and FEA simulations are utilized in testing product prototypes.

7 Describe the differences between oblique, isometric, and perspective 3D drawings.

8 Give the three types of perspective drawing for 3D models.

9 State how exploded views help manufacturers understand the product before the manufacturing stage.



Lesson 2

2D and 3D Design

Link to digital lesson



www.ien.edu.sa

In this lesson, you will be diving into the world of 2D and 3D design. In engineering, both 2D and 3D drawings are used to communicate design information and specifications. 2D drawings, also known as technical drawings or blueprints, are typically used to convey information about a design clearly and precisely, while 3D drawings, also known as 3D models, provide a more realistic representation of an object or structure.

2D and 3D Design

2D (two-dimensional) refers to something that has only length and width but no depth. It can be represented on a flat surface, like a piece of paper or a computer screen. Examples of 2D objects include drawings, paintings, and text on a page.

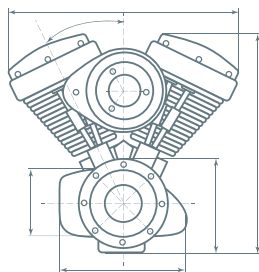
3D (three-dimensional) refers to something that has length, width, and depth. It can be represented in the physical world as an object with volume, such as a cube or sphere. In computer graphics, 3D models and animations are created using mathematical models of 3D objects. These models can be rendered and displayed on a 2D screen, giving the illusion of depth. Examples of 3D objects include sculptures, buildings, and computer-generated characters in movies or video games.

2D



Comparing 2D and 3D Drawings

In engineering, both 2D and 3D drawings are used to communicate design information and specifications. However, there are some key differences between the two.



2D drawings

2D drawings (technical drawings, blueprints) convey precise information about a design and are often used in the manufacturing process to create parts and assemblies and for architectural and construction projects. 2D drawings are usually made using specialized computer-aided design (CAD) software. They are relatively easy to create and share and can be printed or displayed on a computer screen.

3D drawings

3D drawings, also known as 3D models, allow engineers and designers to visualize a design from all angles. They provide a more realistic representation of an object and can be used to simulate the behavior of the final product. 3D drawings are typically created using 3D CAD software and can be rendered to create realistic images and animations. They are often used in product design and development as well as in architectural and construction projects. However, creating 3D drawings can be more complex and time-consuming than creating 2D drawings, and they can also be more resource-intensive to store and share.

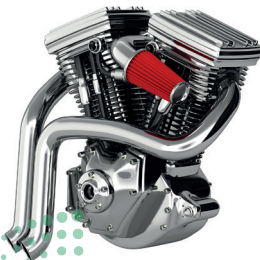


Figure 2.24: 2D drawing and 3D model of V2 engine

In Tables 2.1 and 2.2 we review some examples of 2D and 3D shapes.

Table 2.1: Examples of 2D shapes

Name	Properties	Image
Circle	A shape with a curved line that forms a closed loop. All points on the loop are equidistant from the center point.	
Square	A shape with four straight sides, four right angles, and all sides are equal in length.	
Triangle	A shape with three straight sides and three angles.	
Rectangle	A shape with four straight sides, four right angles, and opposite sides equal in length.	

Table 2.2: Examples of 3D shapes

Name	Properties	Image
Sphere	A shape with a curved surface that is symmetrical around a central point. All points on the surface are equidistant from the center point.	
Cube	A shape with six square faces, twelve edges, and eight vertices.	
Cylinder	A shape with two circular ends and one curved side.	
Cone	A shape with a circular base and a single curved side that tapers to a point.	
Pyramid	A shape with a polygonal base and triangular sides that meet at a single point, the apex.	

INFORMATION

In engineering, 2D and 3D shapes refer to the number of dimensions that a shape or an object has.

Introduction to FreeCAD

FreeCAD is free and open-source 3D CAD (computer-aided design) software. It is used to create and edit models for architecture, engineering, and construction projects. It allows users to create 3D models of buildings, mechanical parts, and other objects using a variety of tools and features. FreeCAD is available for Windows, macOS, and Linux, and it includes a variety of modeling tools like:

- Part Design: for creating 3D mechanical parts and assemblies.
- Arch & BIM: for architectural design and building information modeling.
- Sketcher: for creating 2D sketches that can be extruded into 3D shapes.
- Spreadsheet: for creating and editing tables of data.
- FEM: for finite element analysis of structures and mechanical parts.
- Raytracing: for creating realistic renderings of models.
- Robotics: for designing and simulating robotic arm movements.



3D modeling is the process of creating a digital representation of a three-dimensional object or environment using specialized software.

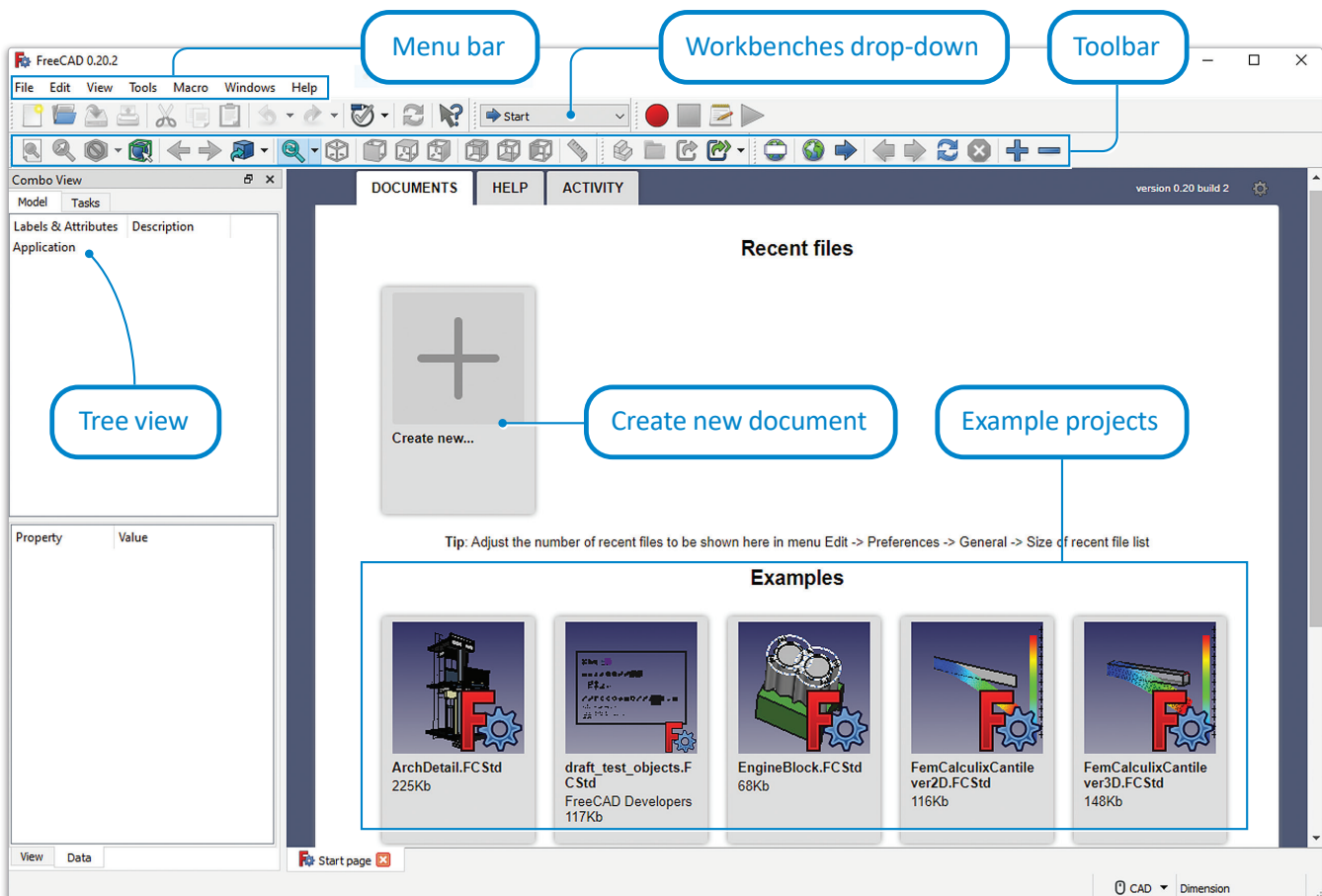


Figure 2.25: The FreeCAD user interface

FreeCAD is a parametric modeler that allows you to change the size and shape of objects and geometric shapes by adjusting their parameters. This makes it easy to make changes to a design and see the results immediately. You can also create assemblies of parts, and create or edit constraints between them, to create more complex models. You can download the software from the following page:

<https://www.freecad.org/downloads.php> and select the version used in the book.

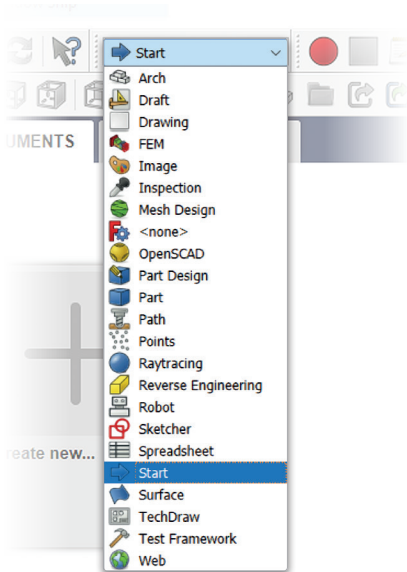
Workbenches

A workbench in the context of computer-aided design (CAD) software is a collection of tools and features that are organized and grouped together to perform a specific task or set of tasks. Workbenches in CAD software provide you with a set of tools that are tailored to a specific type of work or activity. This allows you to quickly and easily access the tools you need for a specific task, without having to navigate through a large set of tools that may not be relevant to your current task.

FreeCAD has a variety of workbenches that are designed for specific tasks and functions. Let's take a look at a list of some of the main workbenches in FreeCAD.

Table 2.3: FreeCAD workbenches

Name	Description
 Spreadsheet  Start  Start	This is the default workbench when FreeCAD starts. It provides a simple interface for opening and creating new documents.
 OpenSCAD  Part Design  Part Design	This workbench is used for creating solid 3D parts and assemblies. It includes tools for sketching, extruding, and revolving 2D shapes to create 3D parts, and tools for creating and editing features such as pads, holes, and chamfers.
 Robot  Sketcher  Sketcher	This workbench is used for creating 2D sketches. It includes tools for creating and editing geometric shapes such as lines, circles, and arcs, as well as tools for applying constraints to define the shape of the sketch.
 Arch  Draft  Draft	This workbench is used for creating 2D drawings and technical drawings. It includes tools for creating and editing shapes such as lines, circles, and polygons and tools for creating dimensions, annotations, and hatching.
 Start  Arch  Arch	This workbench is used for creating architectural elements such as walls, doors, and windows. It includes tools for creating and editing architectural objects and tools for creating and editing building structures.
 Part Design  Part  Part	This workbench is used for creating, editing, and analyzing 3D shapes. It includes tools for creating and editing shapes such as boxes, cylinders, and spheres, as well as tools for performing Boolean operations and for creating and editing meshes.



Tip: Adjust the number of recent files to be shown.



Transforming 2D Shapes into 3D Models

In this lesson you will learn how to use FreeCAD to create 2D shapes and then transform them to 3D. Instead of using predefined 3D shapes from the Part workbench, you will start from scratch.

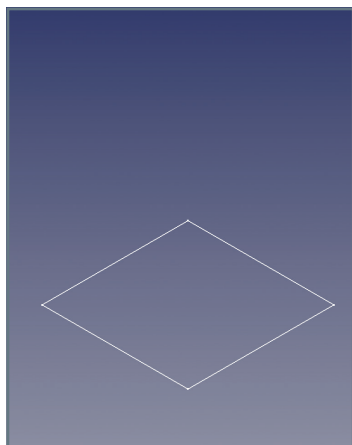
You will start by creating a simple shape like a square, and then you will learn how to turn it into a 3D shape like a cube. You will be using a technique called sketching, where you will draw your shape on a flat surface called a plane. Then, you will learn how to use different tools to draw your shape and how to adjust its size and position. In the process of sketching, you will learn how to apply constraints to the shapes, these constraints are rules that you can use to keep the sketch consistent. Once your 2D shape is ready, you will learn how to give it depth and turn it into a 3D shape. You will use a technique called padding, to add a uniform thickness to a 2D shape.

When creating 3D models, it's often helpful to first create a 2D sketch of the shape you want to make. This allows you to work with the basic shape and proportions of the object before adding the extra dimension. This can save you time and effort in the long run as it's easier to make changes to a 2D sketch than to a fully modeled 3D object. Once you are satisfied with the 2D sketch, you can then use techniques like padding or extrusion to turn it into a 3D shape.

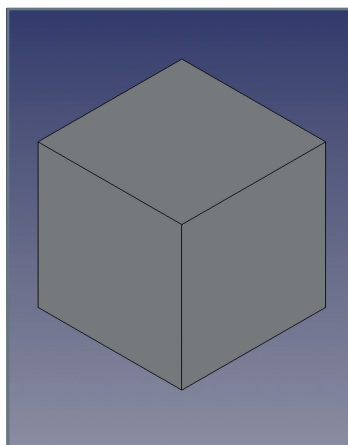
Sketching

Sketching is a technique used in CAD software to create 2D shapes. The basic process of sketching involves creating a 2D representation of an object on a flat surface called a plane. This representation can be used as the basis for creating a 3D model of the object.

Square



Cube



Sketching

Padding

Padding

Padding is a technique used in CAD software to create a 3D object from a 2D shape by adding thickness to it. It is a process of converting a 2D shape into a 3D object by specifying a distance or a thickness value. The resulting object is a solid object with a uniform thickness throughout its entire shape. This technique is commonly used to create objects such as boxes, cylinders, and other basic shapes.

INFORMATION

Padding creates a 3D shape with constant thickness from a 2D shape, while extrusion creates a 3D shape with variable thickness from a 2D shape by stretching it along an axis.

Creating a 2D Shape

Design and Prototyping

Design and prototyping are important concepts in the process of creating and developing products, and they are also important in using 3D modeling software like FreeCAD. FreeCAD allows you to create, edit and modify 3D models, which can be used for both design and prototyping.

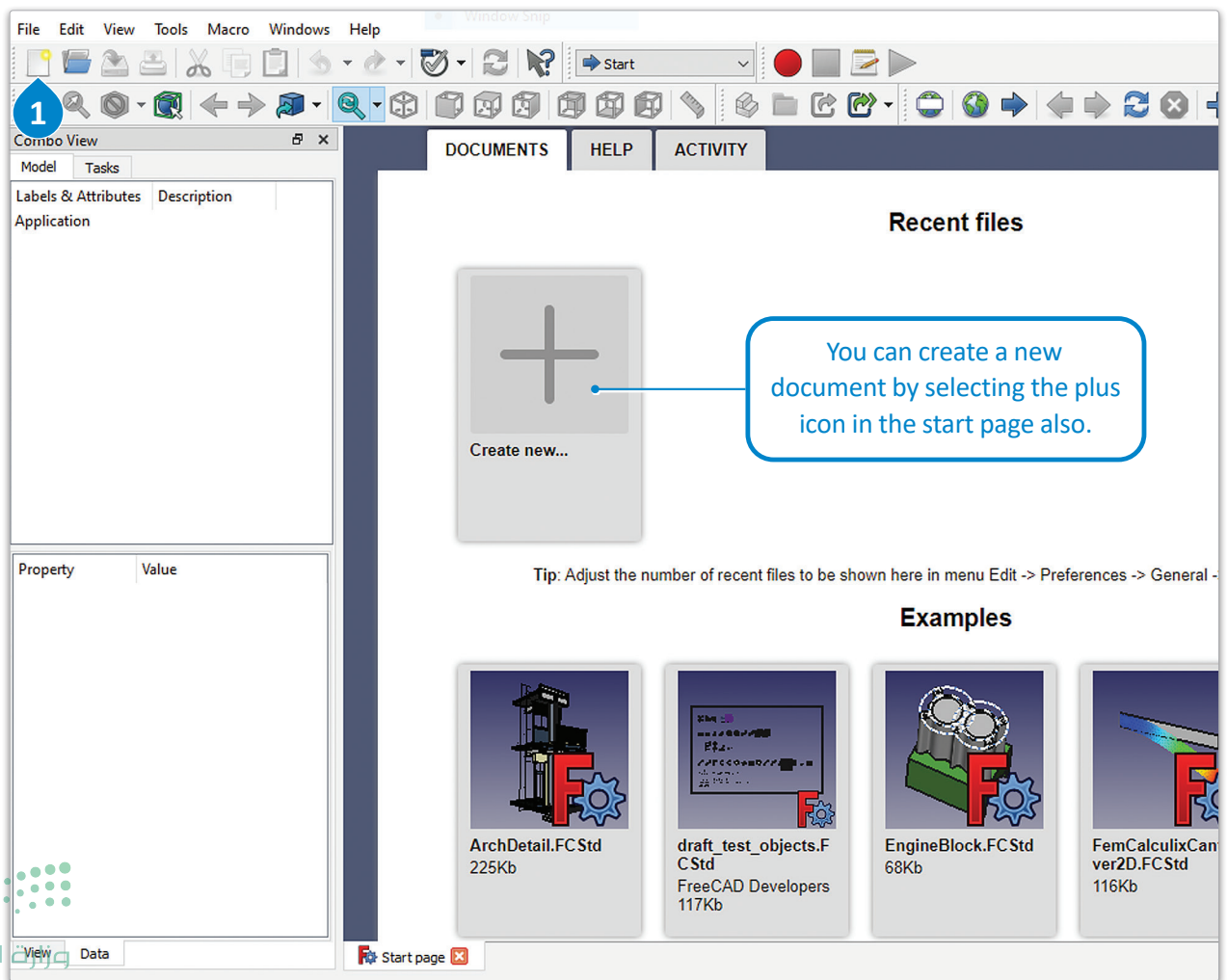
You can create 2D sketches and 3D shapes, perform Boolean operations, and apply different transformations. You can also import and export different file formats, as well using the software to perform simulations and renderings. You can even create a virtual prototype of a design and test it before creating a physical prototype.

Let's create a new document to start working with FreeCAD.

To create a new document:

- > Click on the icon "**New**", from the **toolbar**. ¹
- > From the **workbench drop-down** menu, select the "**Part Design**" workbench. ²

Using FreeCAD is like using a digital pencil and paper, but instead of drawing on paper, you are drawing on the computer.



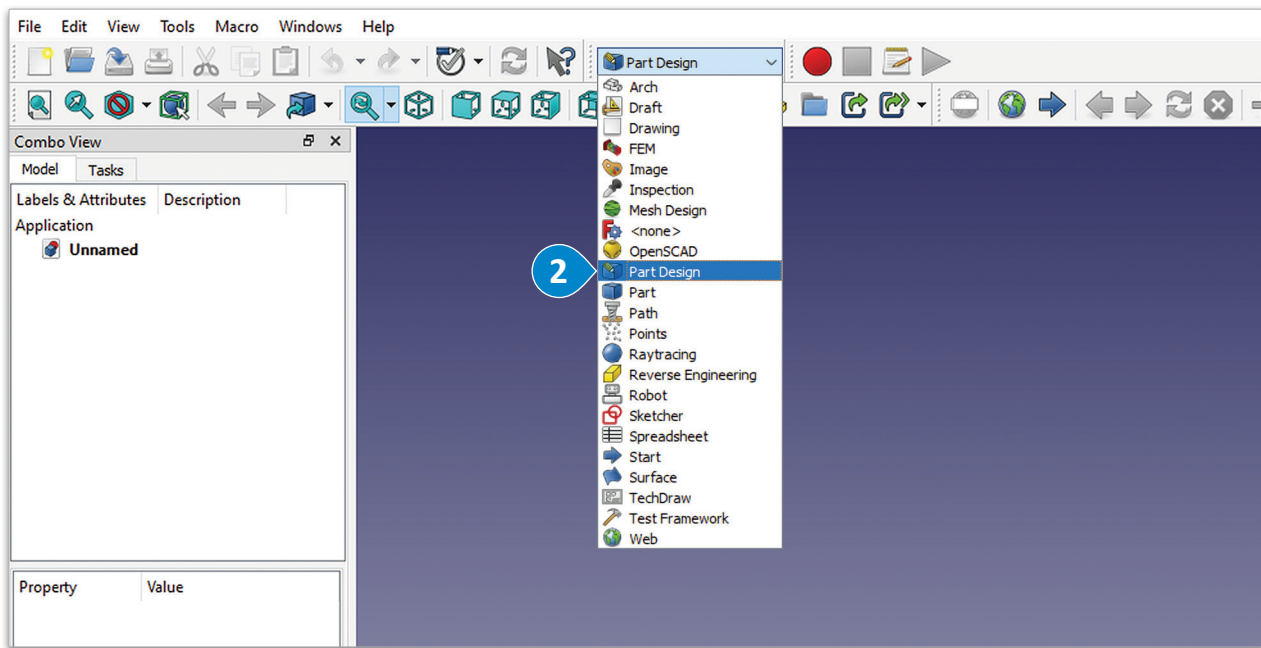


Figure 2.26: Creating a new document and Selecting the "Part Design" workbench

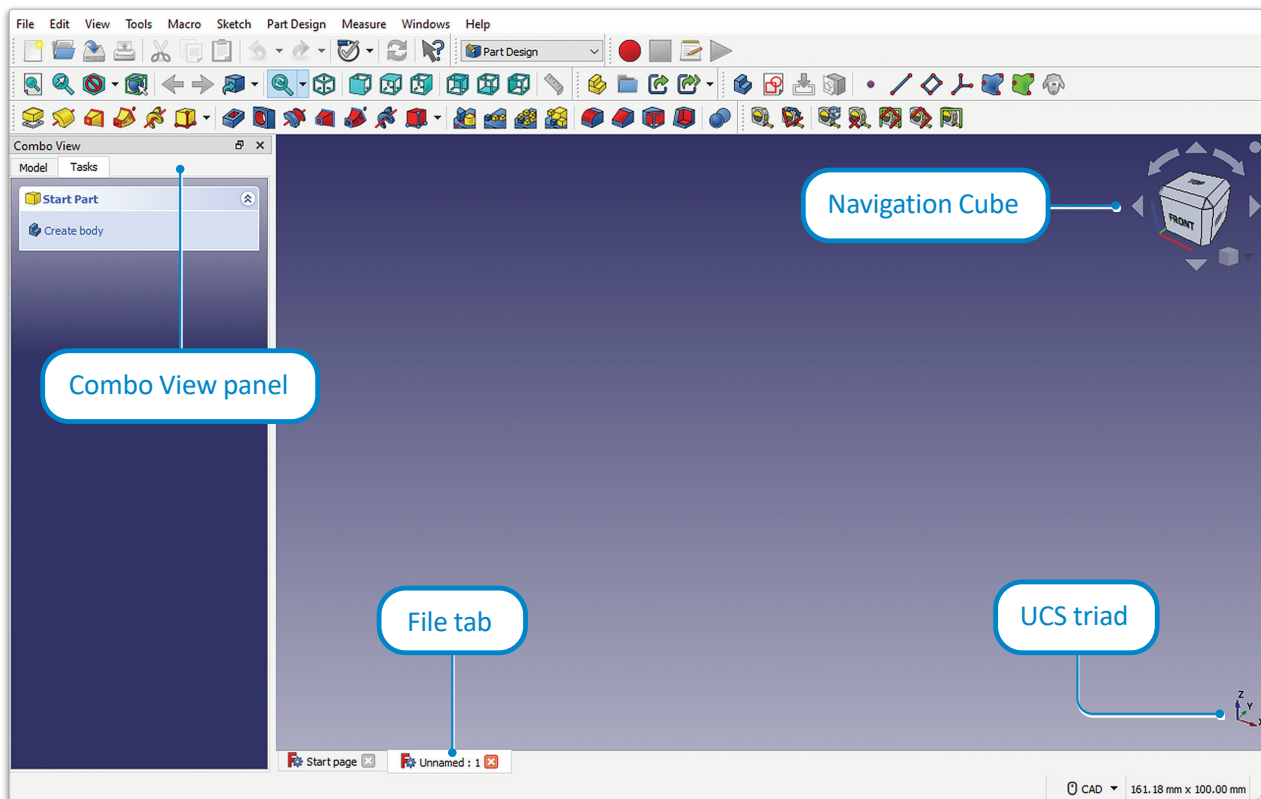


Figure 2.27: User interface

The UCS (User Coordinate System) triad in FreeCAD is a visual representation of the three axes (X, Y, and Z) of the 3D coordinate system.



Creating a Body

In the context of CAD software, a body refers to a 3D representation of a physical object. It is a digital model that can be created, edited, and manipulated using the tools and features of the CAD software. Bodies can be simple or complex and can be composed of one or more parts. In most CAD software, a body is a solid object that has volume and can be represented by a set of mathematical equations and vertices. Creating a body in CAD software is an essential step in the design and manufacturing process. It allows the user to visualize, analyze, and communicate the design effectively, and it helps to ensure the manufacturing process is efficient, accurate and cost-effective.

To create a body in FreeCAD, you can use a variety of tools depending on the specific requirements of your project. You will create a body using the Part Design workbench.

To create a body:

- > From the **Start Part** menu in the **Tasks** tab, click **Create body**. ①
- > From the **Start Body** tab, click **Create sketch**. ②

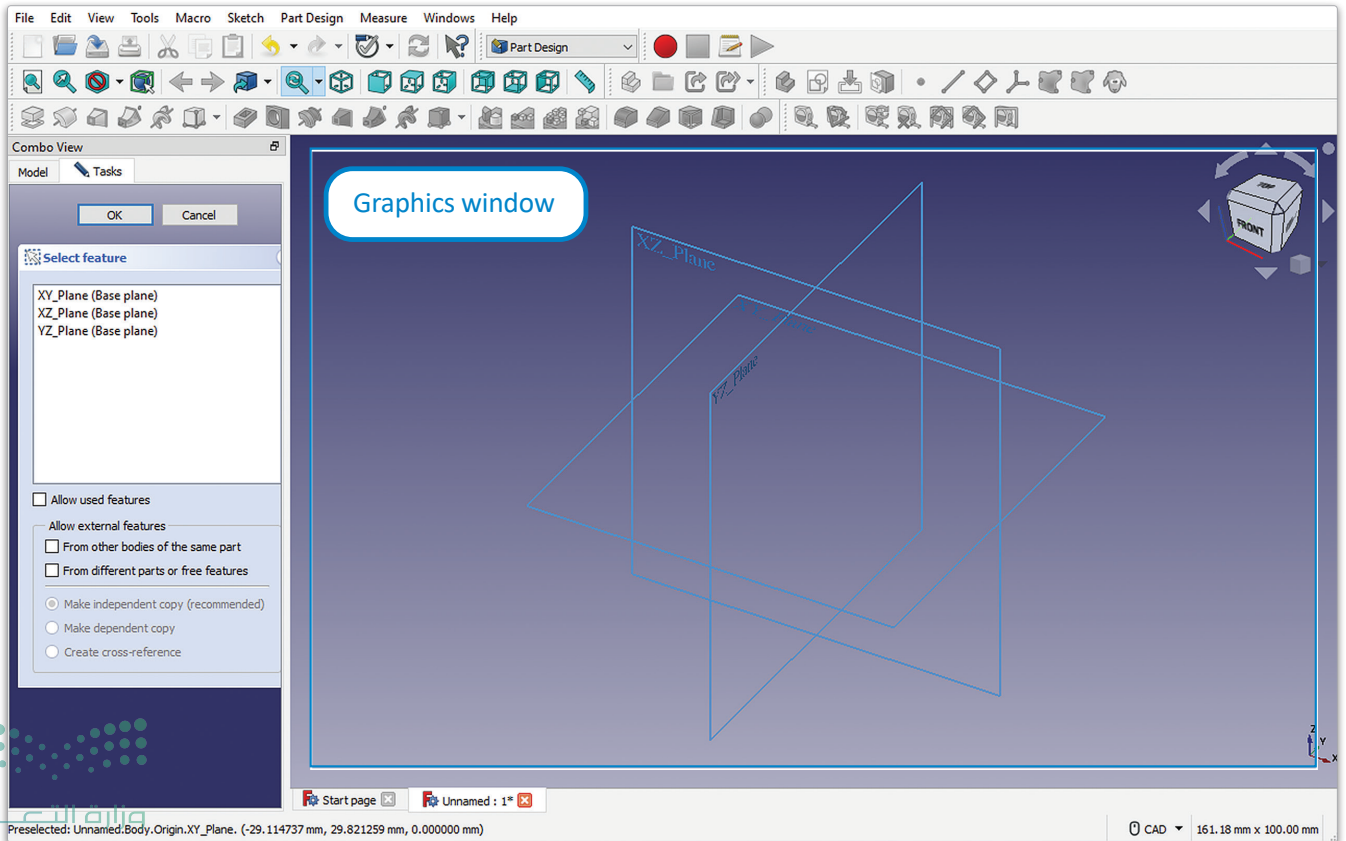
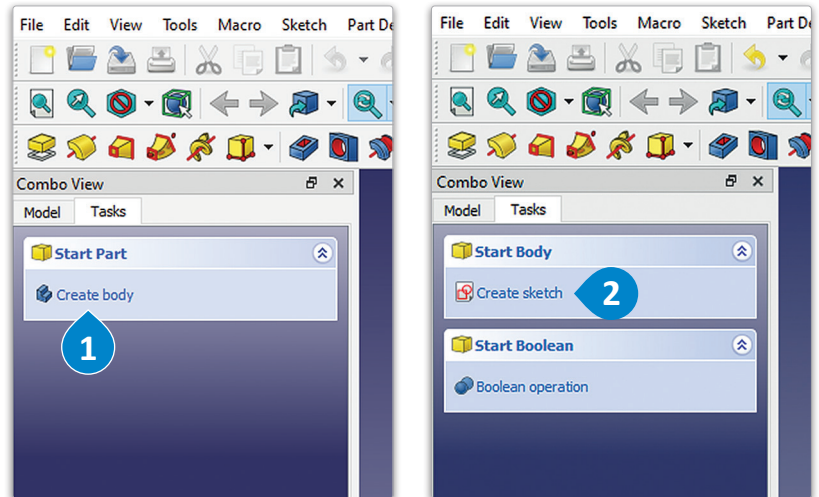


Figure 2.28: Creating a body

Planes

A plane is a flat 2D surface that can be used as a reference for creating and positioning objects in 3D space. Planes are used in the Sketcher workbench to create 2D sketches that can be extruded, revolved, or padded into 3D shapes. They use a global coordinate system which is a three-dimensional reference framework that uses X, Y, and Z coordinates to identify the position of any point in space relative to a fixed origin point.

FreeCAD has 3 main planes: XY, YZ, and XZ planes each of them can be used for different purposes.

- XY Plane: This is the default plane that is used when creating a new sketch. It is a horizontal plane that is parallel to the XY plane of the global coordinate system.
- YZ Plane: This plane is parallel to the YZ plane of the global coordinate system. It can be useful for creating sketches that are oriented vertically.
- XZ Plane: This plane is parallel to the XZ plane of the global coordinate system. It can be useful for creating sketches that are oriented horizontally.

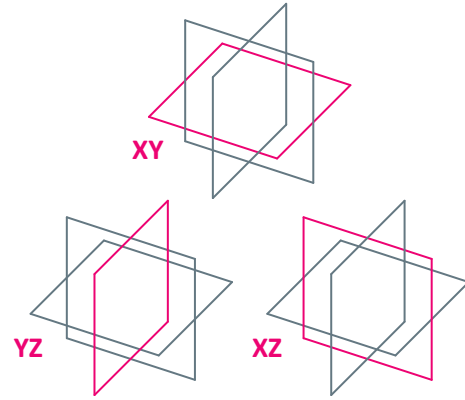


Figure 2.29: Representation of FreeCAD planes

Figure 2.30 shows the 3 main planes.

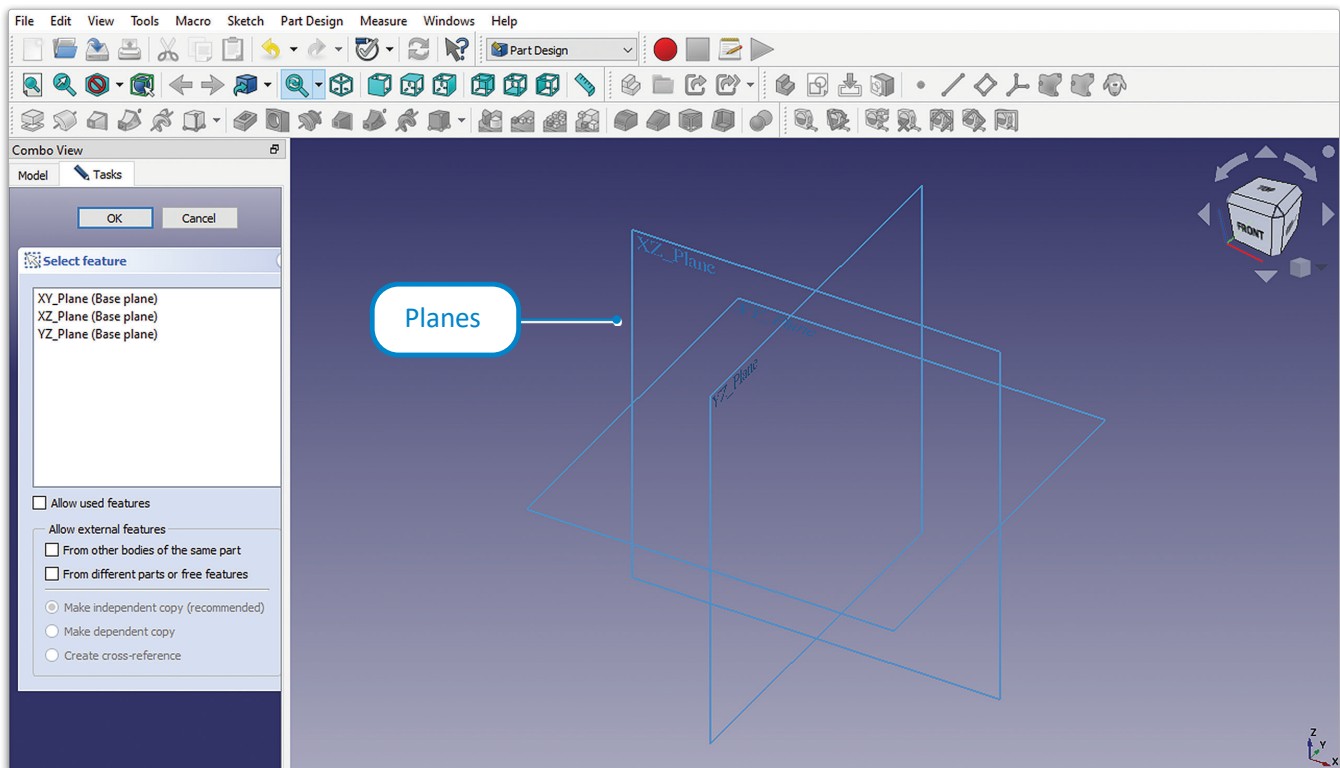


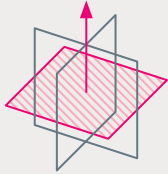
Figure 2.30: Planes

INFORMATION

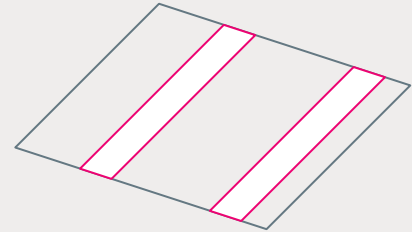
There is a plane called the user-defined plane that is created by the user and allows you to create a reference surface at any location and orientation within the 3D space vector.

Let's take a look at some examples to achieve a better understanding of planes in FreeCAD.

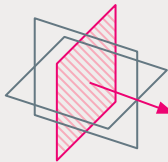
XY plane



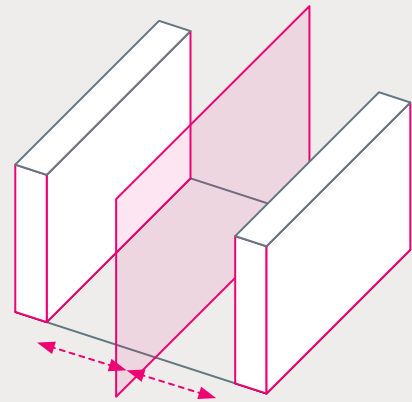
The XY plane can be used as a reference surface for creating 2D sketches. For example, if you want to create a 2D drawing of a floor plan, you can create a new sketch on the XY plane, and use the sketching tools to draw the walls, doors, and other features of the floor plan.



YZ plane



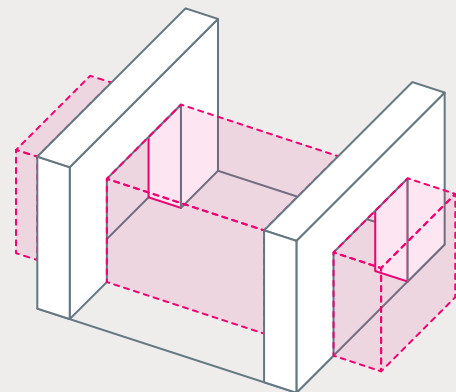
The YZ plane can be used as a reference surface for aligning objects and shapes. For example, if you are creating an assembly of multiple parts, you can create a plane parallel to the YZ plane and align the parts to it. This will ensure that the parts are correctly positioned relative to each other.



XZ plane



The XZ plane can be used as a reference surface for creating cross-sections of 3D models. For example, if you want to create a cross-section of a 3D model of a building, you can create a new plane parallel to the XZ plane and use it as a cutting plane to create a section of the building.



These are just a few examples of how the planes in FreeCAD can be used. Depending on the features of the CAD software used, there may exist many more possibilities. But the main idea is that each plane can be used as a reference surface for different purposes. The XY plane is mainly used for creating sketches, the YZ plane is mostly used for alignment, and the XZ plane is mainly used for creating cross-sections.

Now you will choose the XY plane in FreeCAD by selecting the XY plane from the list of planes. This will create a new sketch parallel to the XY plane. Think of it like drawing on a piece of paper lying on your desk. The paper is the XY plane, and the drawing is our sketch.

To choose a plane:

- > From the **Tasks** tab in the **Combo View**, click **XY_Plane**. **1**
- > From the **Tasks** tab in the **Combo View**, click **OK**. **2**

FreeCAD automatically changes the workbench from "Part Design" to "Sketcher" when creating a new sketch.

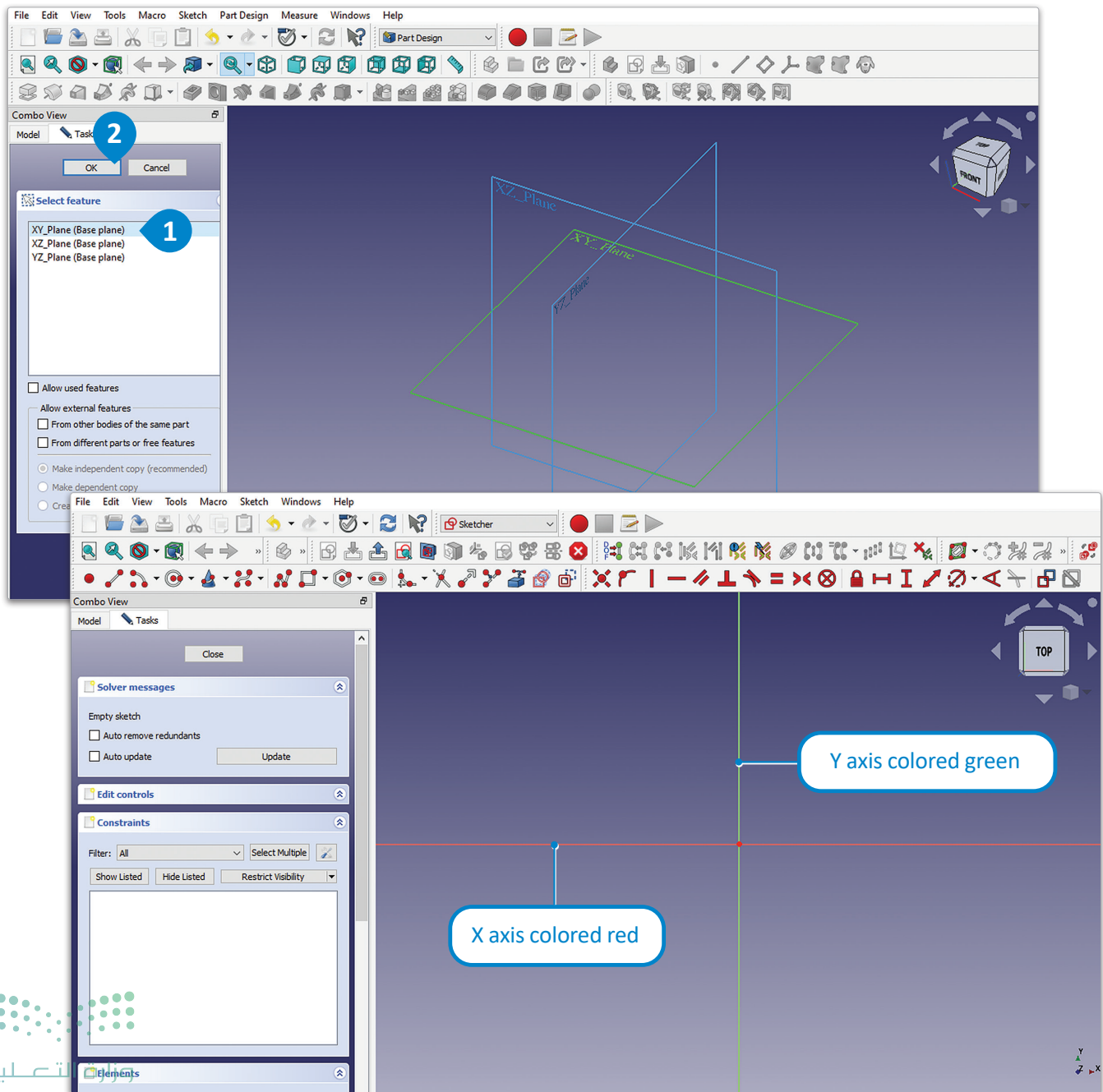


Figure 2.31: Choosing a plane

The Grid

Enabling the grid when using FreeCAD is essential because it allows you to create and modify objects with greater precision and accuracy. The grid is a set of lines that are displayed on the screen. It helps you to align the points, edges, and faces of your object with respect to the grid lines. This can make the modeling process more accurate and more manageable.

To enable the grid:

- > From the **Tasks** tab, click **Edit controls**. **1**
- > From the **Tasks** tab in the **Edit controls** tab, select **Show grid** **2** and then select **Grid snap**. **3**
- > From the **Tasks** tab, click **Edit controls** to minimize the tab. **4**

Grid snap is a feature that allows you to snap the cursor to the grid lines.

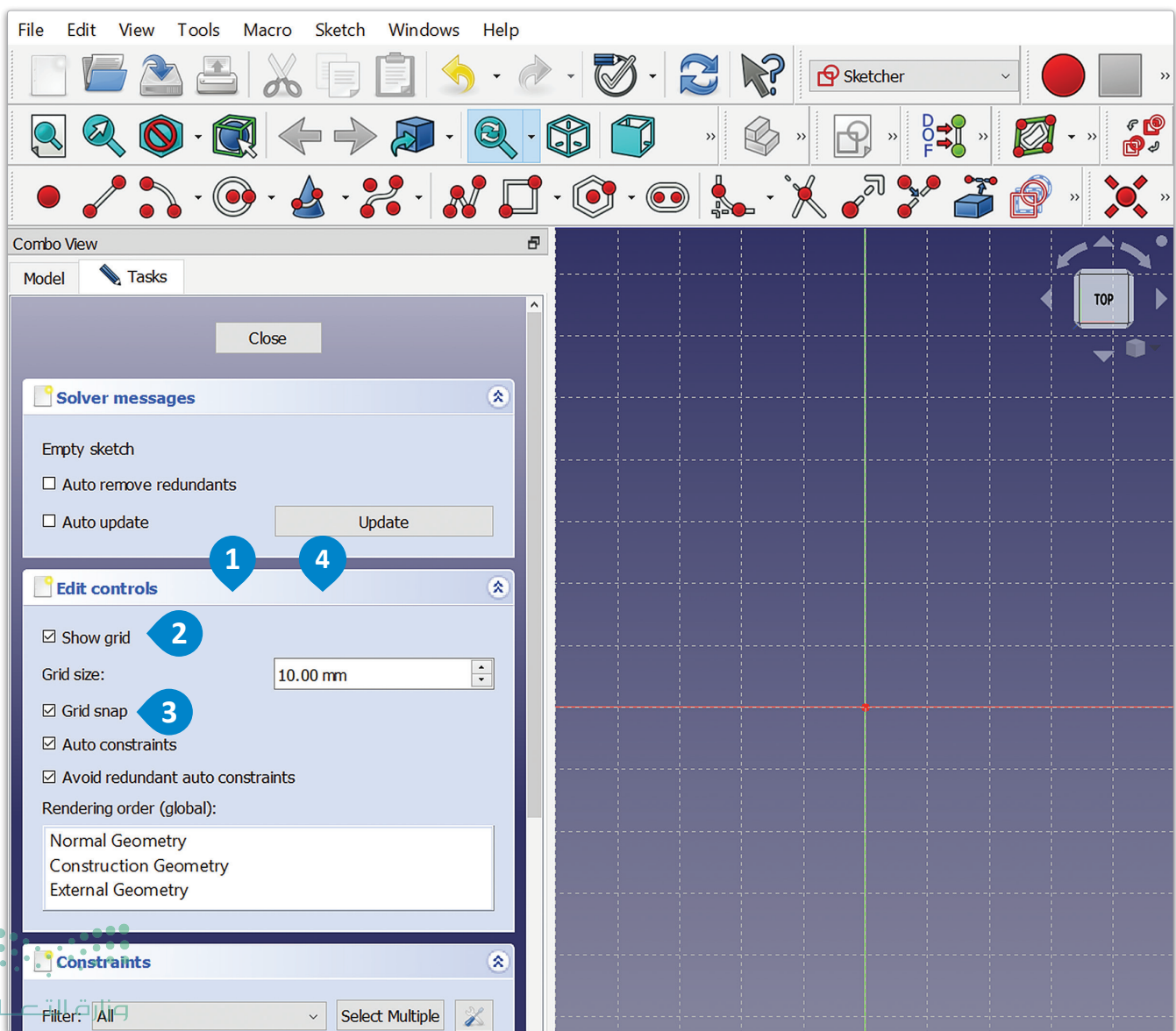
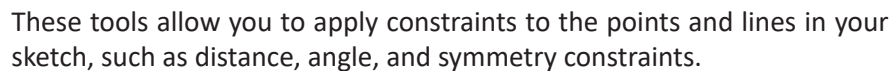
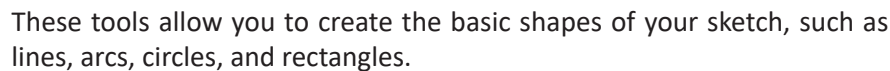
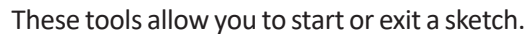


Figure 2.32: Enabling the grid

To create a 2D shape, you will work on the Sketcher workbench. The Sketcher provides a set of tools and features that allow you to create and edit 2D sketches and apply geometric constraints to the points and lines in the sketch. Before we start creating the square, let's have a look at some of the main tools on the Sketcher workbench toolbar:

These tools allow you to control the view of the sketch by, for example, zooming, panning, and rotating.



- **Rectangle:** This option creates a standard rectangle. You can define the rectangle by clicking on a point and dragging the cursor to set the opposite corner of the rectangle, or by clicking on two diagonal corners to define the rectangle.
- **Centered rectangle:** This option creates a rectangle with the center point defined by you. You can set the center point and the distance from the center to the corners to create the rectangle.
- **Rounded rectangle:** This option creates a rectangle with rounded corners. You can set the rounding radius on the corners to create a rectangle with corners rounded according to your requirements.



To create a rectangle:

- > From the **toolbar**, select the create **rectangles** tool. **1**
- > Click on the sketch to set the first corner of the rectangle. **2**
- > Move the cursor to set the opposite corner of the rectangle, and click again to create the rectangle. **3**

You can deselect a tool by right clicking on the empty space outside of the shape. This will deactivate the tool, and you will be able to select another tool.

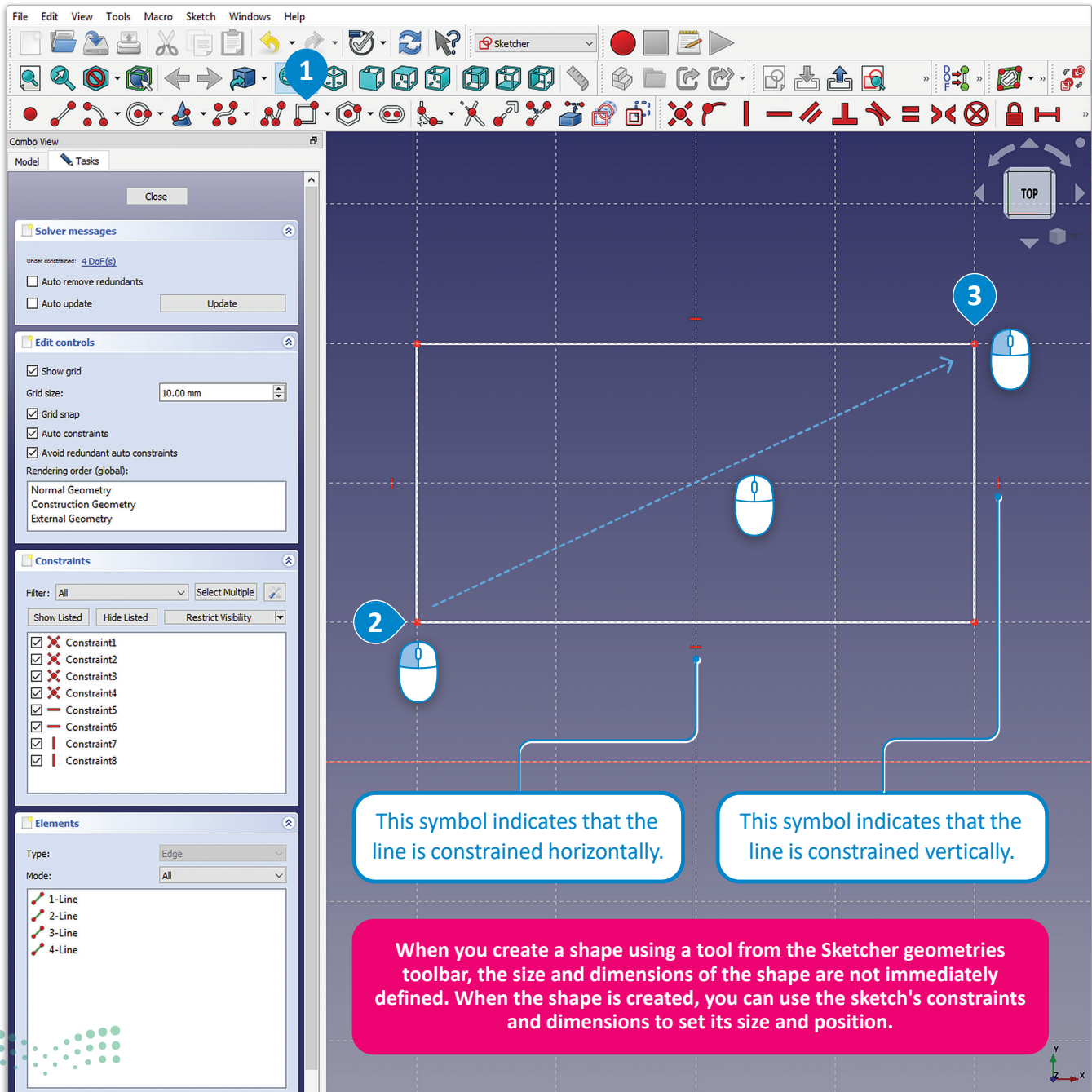


Figure 2.33: Creating a rectangle

Object Constraints

Constraints are used to define the geometric properties and relationships between different elements of a sketch, such as points, lines, and shapes. Constraints are used to define the behavior of an object and to make sure that it maintains its shape and position as you make changes to it. When you create a shape in FreeCAD, for example a rectangle, it has some predefined constraints. These constraints are automatically applied to the rectangle to ensure that it maintains its geometric properties and can be modified and manipulated predictably.

Degrees of Freedom (DoF)

The Degrees of Freedom (DoF) refers to the number of independent variables a sketch or a part has, determining the number of directions in which it can move or be modified. The DoF is determined by the number of geometric constraints applied to a sketch or part and the number of dimensions that define it.

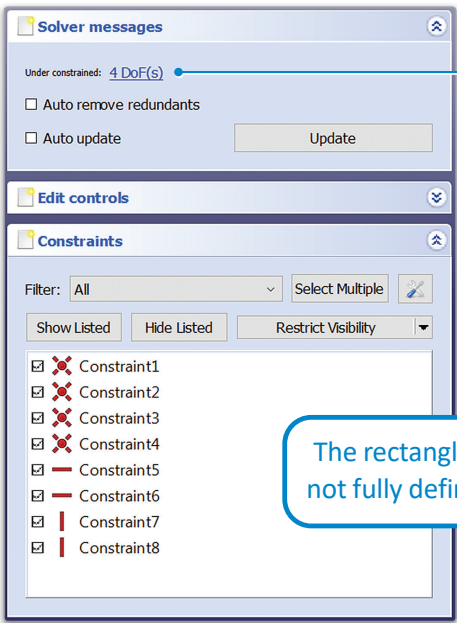
Through Table 2.4, you can learn in detail about some of the constraint tools in FreeCAD.

Table 2.4: Constraint tools

Icon	Tool
	Constrain coincidence: This tool is used to align two points or lines together, it ensures that the selected points or lines are coincident (in the same location).
	Constrain point onto object: This tool is used to constrain a point to lie on a specific object.
	Constrain horizontally: This tool is used to make a line horizontal, it ensures that the selected line is parallel to the x-axis.
	Constrain vertically: This tool is used to make a line vertical, it ensures that the selected line is parallel to the y-axis.
	Constrain equal: This tool is used to constrain two lines, arcs or circles to have the same length, radius or angle between them.
	Constrain symmetry: This tool ensures that an object is symmetrical about a certain point or line.
	Constrain horizontal distance: This tool is used to set a fixed horizontal distance between two points or lines, it ensures that the selected points or lines maintain a fixed horizontal distance apart.
	Constrain vertical distance: This tool is used to set a fixed vertical distance between two points or lines, it ensures that the selected points or lines maintain a fixed vertical distance apart.
	Constrain Angle: This tool ensures that two lines maintain a fixed angle between them.

Constraint

A constraint is a rule or condition applied to an object to control how it can be modified or moved.



The rectangle is not fully defined.

A fully defined sketch with 0 DoF(s) is required to use the tools that create 3D shapes.

The order in which you apply constraints to an object in FreeCAD can affect the object's behavior and the sketch's feasibility. It's better to apply the most basic constraints first, such as fixing the position of a point or the length of a line, and then add more complex constraints as needed.

To turn your rectangle into a square, you have to constrain the lengths of two adjacent sides to be equal. You should start by applying a distance constraint to one side and then use that side as a reference to constrain the adjacent side.

To constrain horizontal distance:

- > From the **Constraints toolbar**, select the **Constrain horizontal distance** tool. **1**
- > Click on the upper edge of the rectangle. **2**
- > Set the **Length** to **50 mm**, **3** and click OK. **4**

The navigation style for interacting with and moving through a 3D model in FreeCAD.

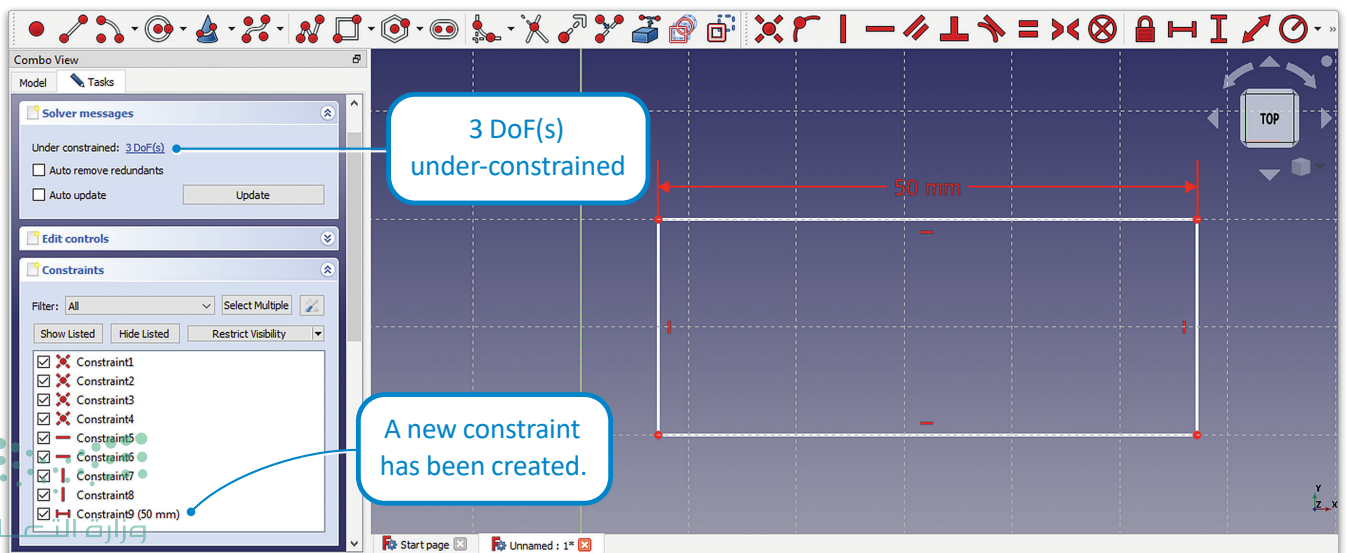
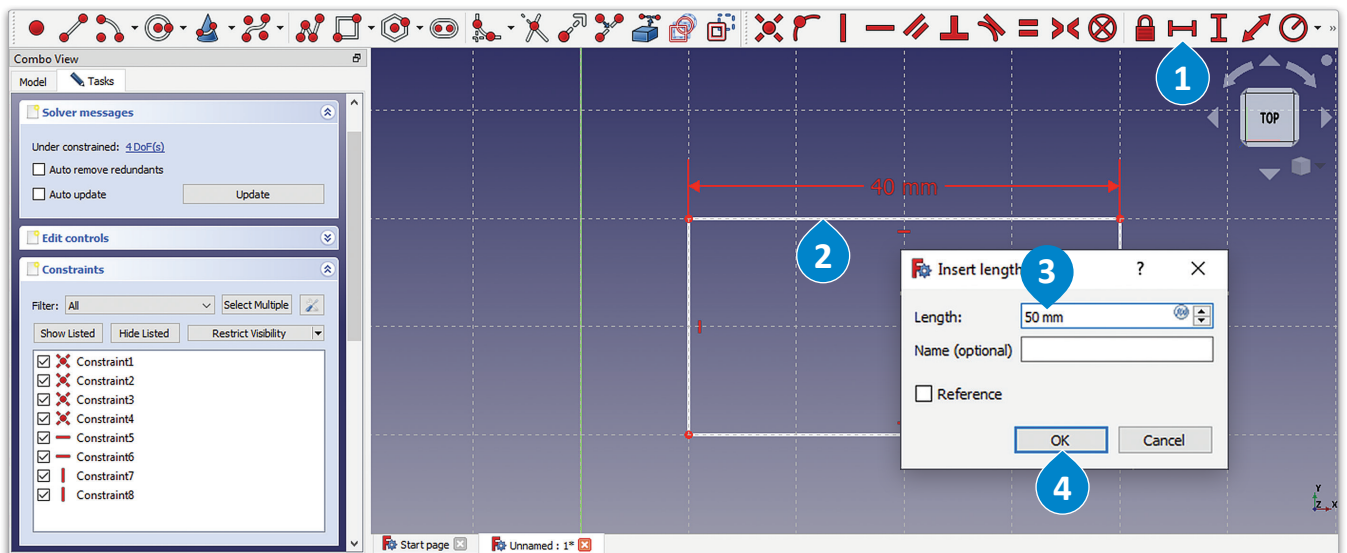
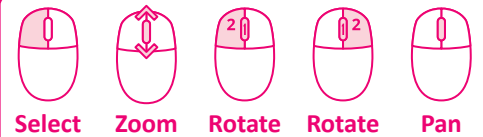


Figure 2.34: Constraining horizontal distance

- In order to create the square you will use the Constrain equal tool to make the edges of the rectangle equal.

To make the sides equal:

- > From the **toolbar**, select the **Constrain equal** tool. ①
- > Select the upper edge, ② and then select the right edge of the rectangle. ③

When you choose a tool and hover the mouse cursor over a line, the line turns yellow, indicating that it is preselected and can be selected by clicking on it. When you click on the line, it turns green, indicating that the line is now selected and can be modified or used by the current tool.

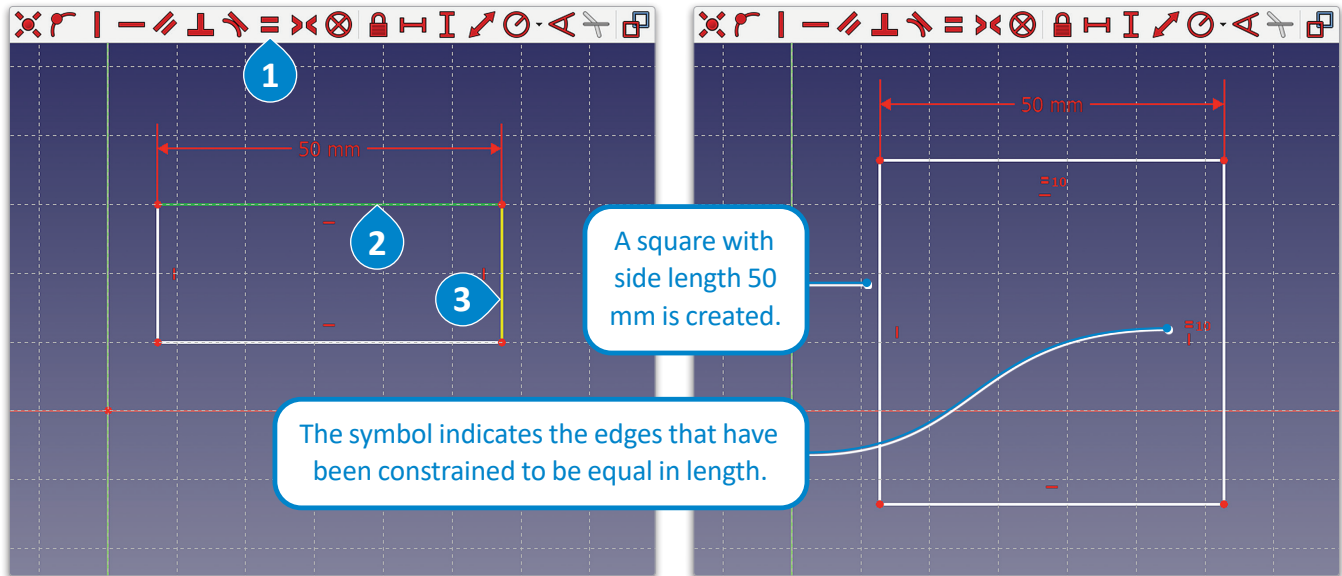


Figure 2.35: Making the sides equal

- ✗ Finally, to have a fully constrained square you will need to use the Constrain coincident tool to constrain the position of one corner of the square to the intersection of the axes.

To constrain points:

- > From the **toolbar**, select the **Constrain coincident** tool. ①
- > Select the lower left corner of the square ② and then select the center of the axis. ③

Once a square is fully constrained, it is not possible to change its shape or size without breaking one or more of the constraints.

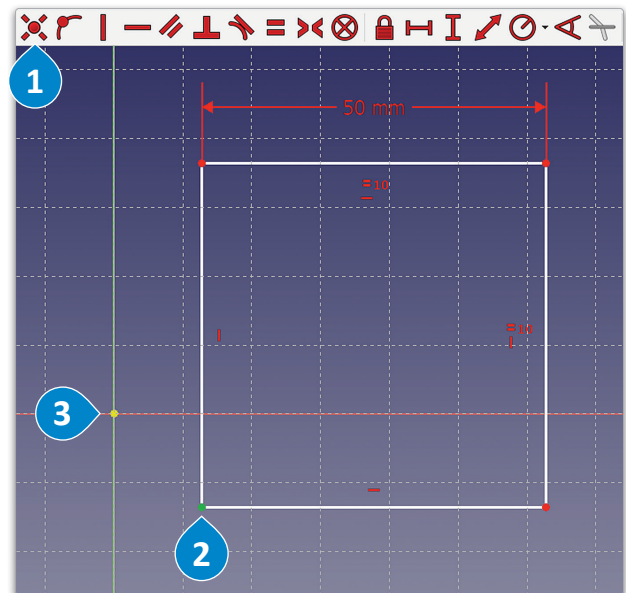


Figure 2.36: Constraining points



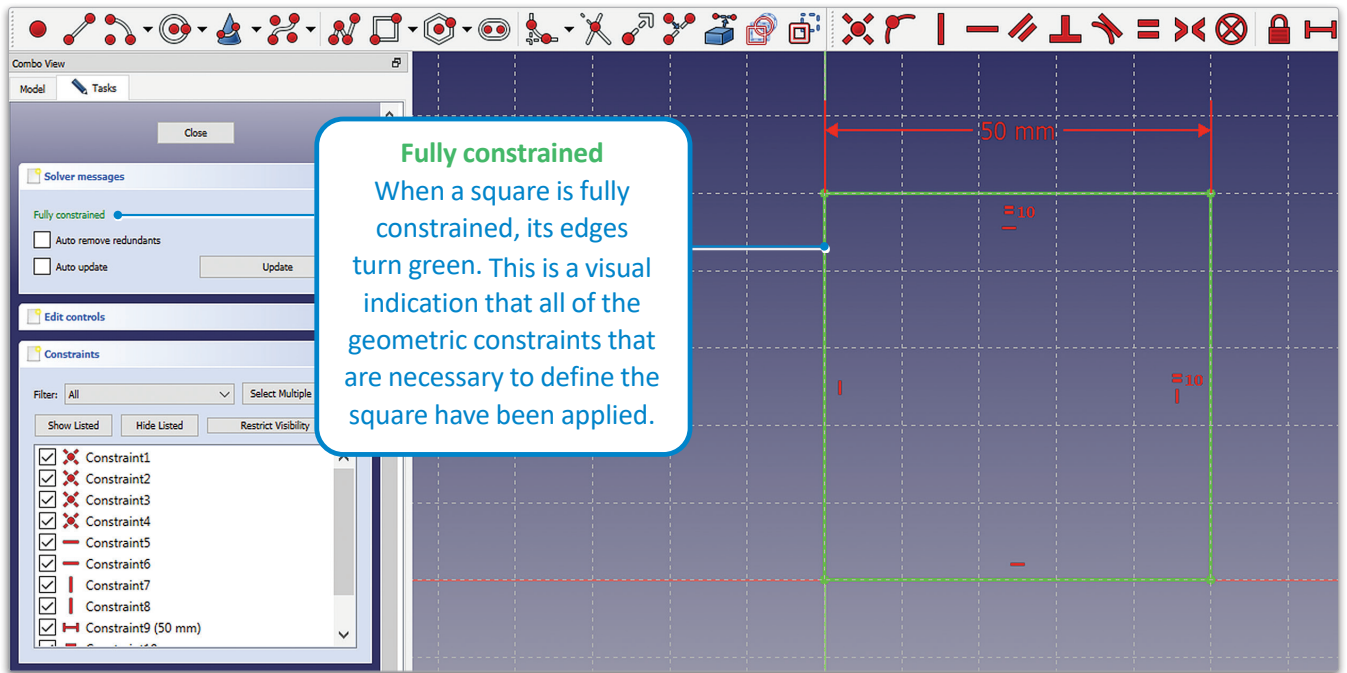


Figure 2.37: Fully constrained shape

Now that you have fully constrained the square you can close the sketch.

To close the sketch:

- > From the **Tasks** tab, click **Close**. **1**
- > From the **Combo View**, click the **Model** tab. **2**

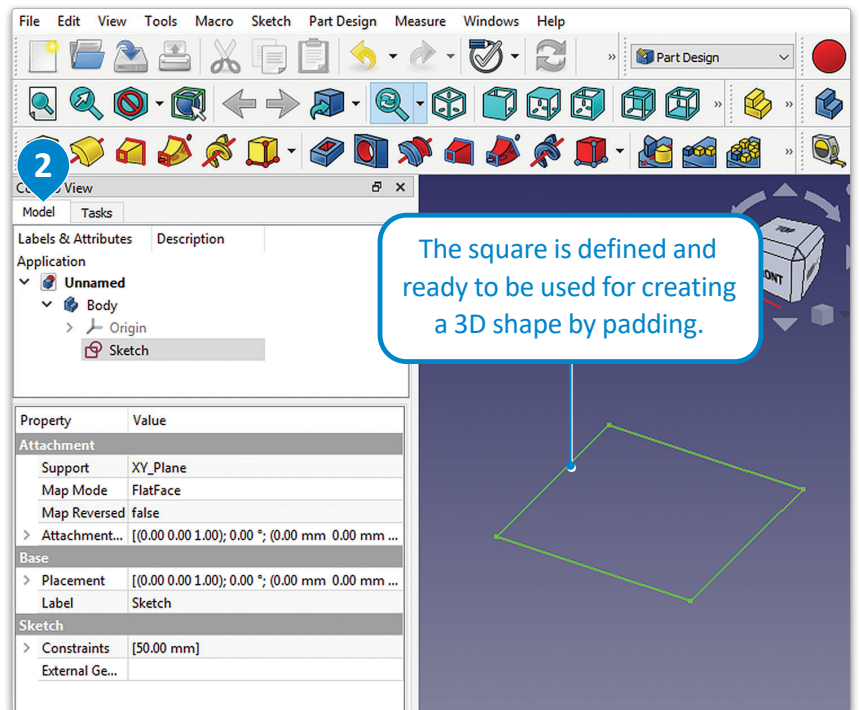
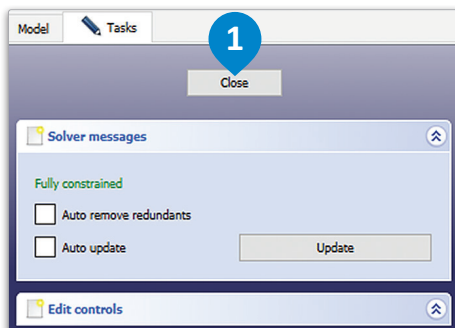


Figure 2.38: Closing the sketch

INFORMATION

A fully constrained square indicates that the shape is ready to be used as a base for further operations, like creating a 3D shape by extrusion or using it as a reference for other shapes or measurements.

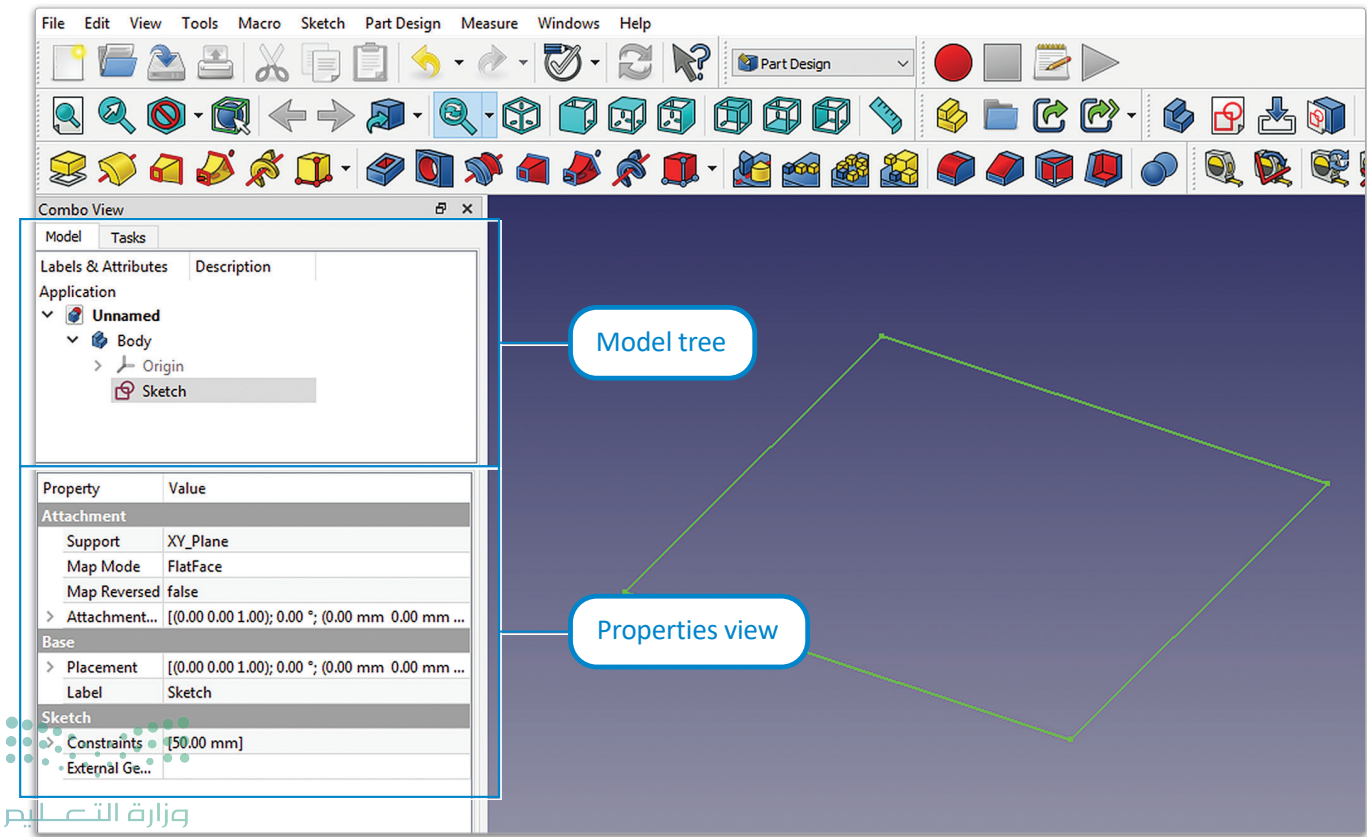
When you have finished applying constraints to a square and left the sketch, the changes you made will be reflected in the Model tab, where you can see the overall structure of your design.

You will see the square you created as a new addition in the Model tree, with the same properties and constraints that you applied to it in the sketch. The square will have a unique name, and the properties of the object will be displayed in the Properties view, where you can see the object's length, width, position, and other characteristics.

If you want to use the square as a reference for other shapes or features, you can select it from the model tree and use it as a base for your next operations.

Table 2.5: The Model tab

Name	Description
Model tree	The Model tree is a hierarchical view of all the objects in your design, it shows the structure of your model, starting from the top level, which is the document, and going down to the individual shapes, parts, and features.
Properties view	The Properties view is a panel that shows the properties of the selected object. It will display the name, position, size, and other characteristics of the object. You can use the Properties view to change the properties of the object.



Creating a 3D Shape

Padding

Now that you have finished creating the square, you will proceed to turning it into a 3D cube by using the padding technique. Padding is a technique that allows you to take a 2D shape, like a square, and give it depth by adding thickness to it. This creates a 3D shape, like a cube, that has volume and can be viewed and manipulated in 3D space.

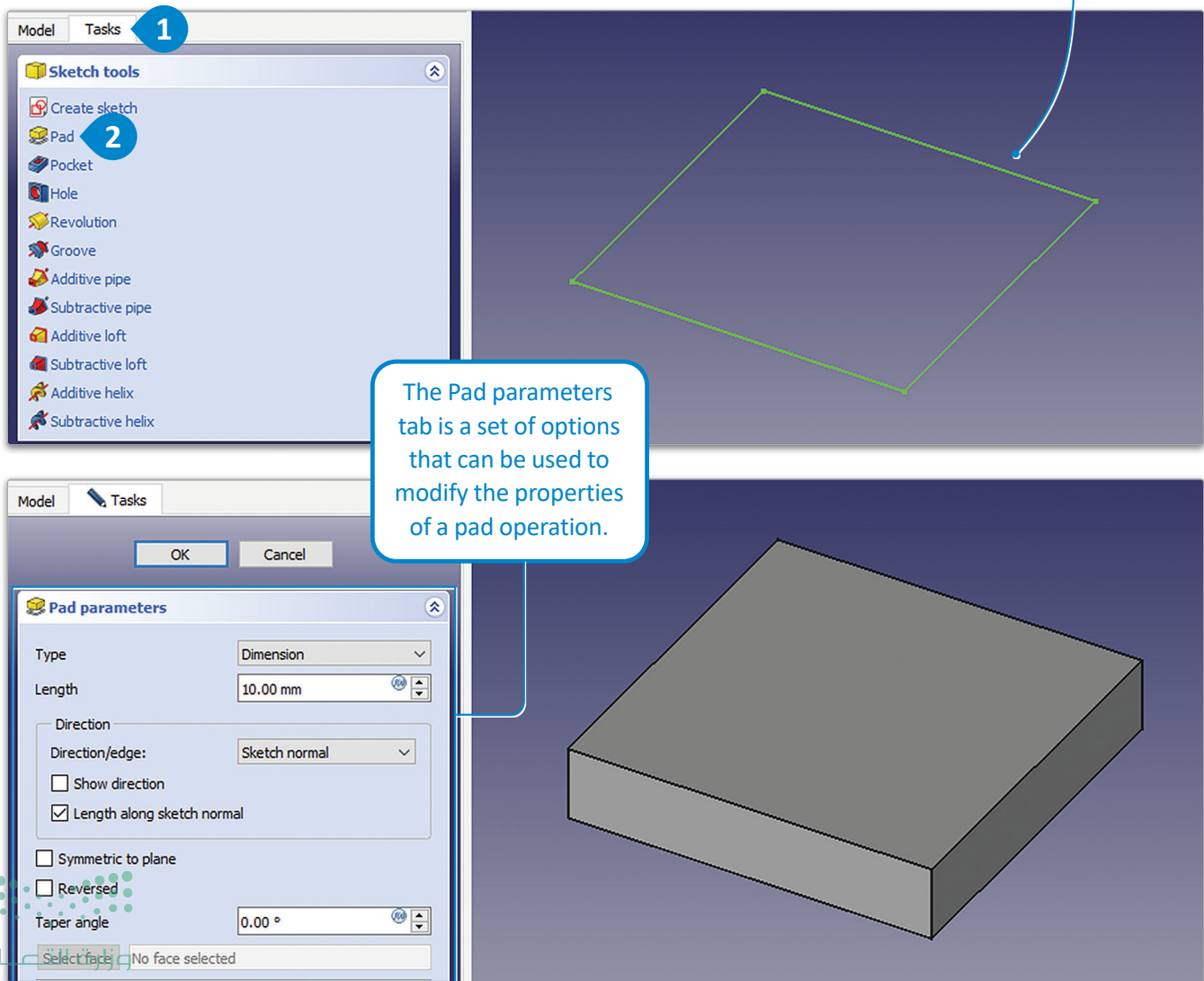
So let's return to the Tasks tab to create the 3D shape.

A 3D cube, represented in the 3D view, can be used for further operations like adding details, creating assemblies, or simulating the object.

To create a 3D shape:

- > From the **Combo View**, select the **Tasks** tab. **1**
- > From the **Tasks** tab, click **Pad**. **2**
- > From the **Tasks** tab, change the length to **50 mm**, **3** and click **OK**. **4**

The green color indicates that the shape is selected.



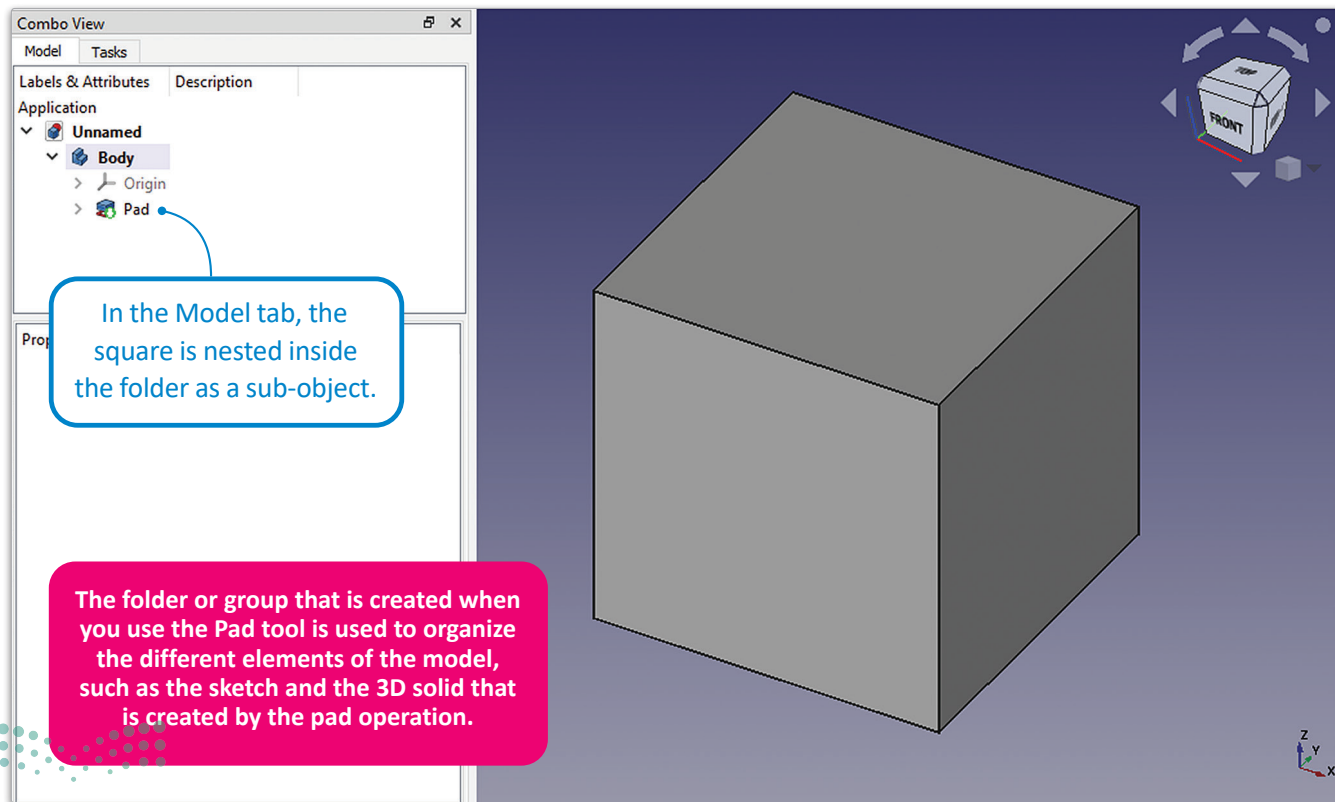
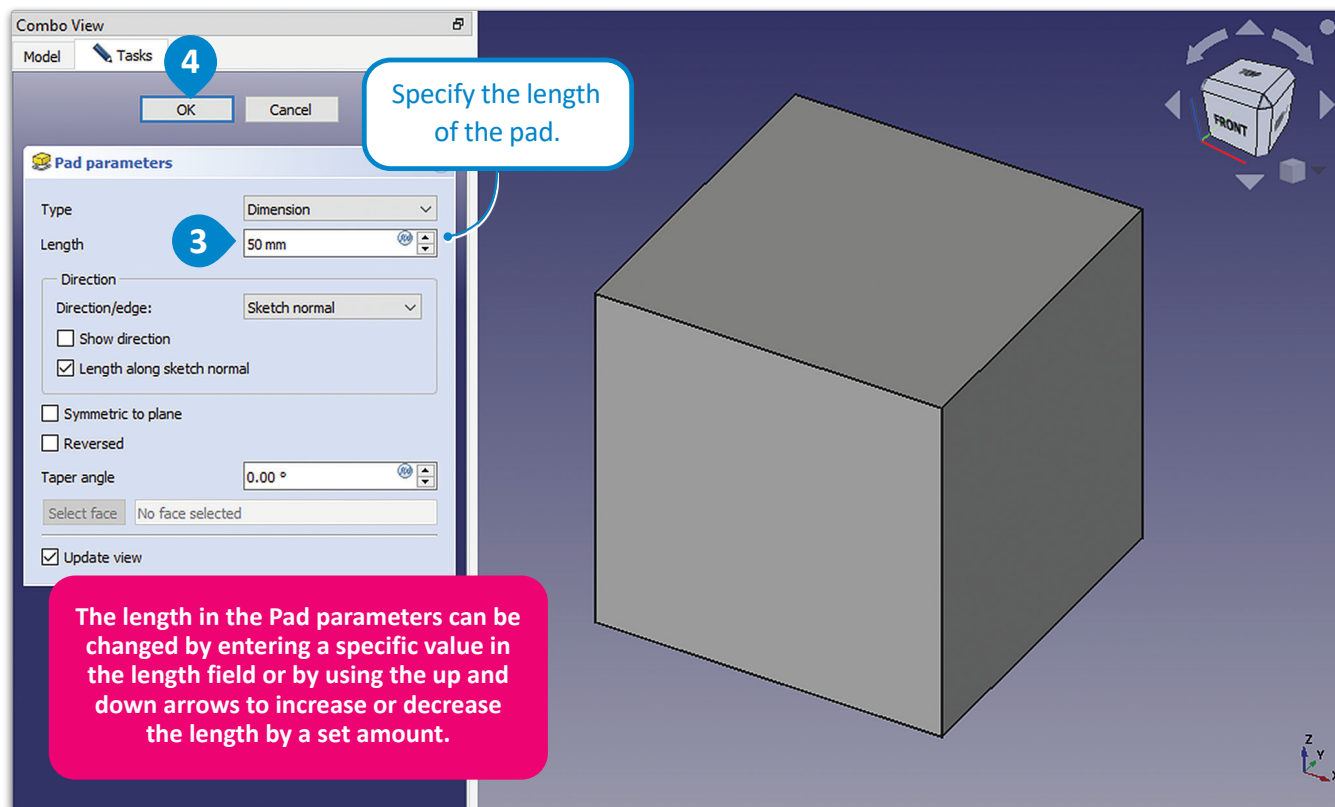


Figure 2.39: Creating a 3D shape

Now that you have created your 3D model let's take a look at the different 3D views that can give you a better understanding of your 3D model.

3D Views

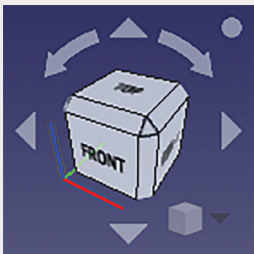
In 3D modeling and design, a 3D view displays and interacts with a 3D model from a specific perspective. 3D views allow designers and engineers to view and manipulate their models from different angles. In FreeCAD, several different 3D views can be used to navigate and manipulate the 3D object.

Table 2.6: 3D views

Name	Icon	Description
Isometric		This view displays the 3D model from a 45-degree angle, providing a more realistic representation of the object's shape and size.
Front		This view displays the model from the front, with the X and Y axes visible.
Top		This view displays the model from the top, with the X and Z axes visible.
Right		This view displays the model from the right side, with the Y and Z axes visible.
Rear		This view displays the model from the back, with the X and Y axes visible.
Bottom		This view displays the model from the bottom, with the X and Z axes visible.
Left		This view displays the model from the left side, with the Y and Z axes visible.

Another tool that you can use to change the view is the Nagivation Cube. It is a feature in 3D modeling software that allows you to quickly and easily change the view of your model. By clicking and dragging on the different faces of the cube, you can rotate your model to view it from different angles.

The Navigation Cube can be helpful when working on a complex model and you need to see it from different perspectives to make adjustments or check for errors.



Exercises

1

Read the sentences and tick ✓ True or False.	True	False
1. 2D designs only have length and width, but no depth.	☐	☐
2. 2D drawings are used to convey information about a design in a precise and clear way.	☐	☐
3. 3D models can be used to simulate the behavior of the final product.	☐	☐
4. A triangle is a 3D shape with three straight sides and three angles.	☐	☐
5. Once a square is fully constrained, it is not possible to change its shape or size without breaking one or more of the constraints.	☐	☐
6. The Model tree is a hierarchical view of all the objects in a design, showing the structure of the model from the top level down to the individual shapes, parts, and features.	☐	☐
7. The Properties view is a panel that shows the properties of the selected object, including the object's length, width, position, and other characteristics.	☐	☐
8. The 3D views allow designers and engineers to only view their models and not manipulate them.	☐	☐
9. The Navigation cube is a feature in 3D modeling software that allows you to quickly and easily change the view of your model.	☐	☐
10. The Isometric view in FreeCAD displays the 3D model from a 90-degree angle.	☐	☐

2

Explain the purpose and use of the Constrain coincident tool.



3 Choose the correct answer below.

- Which tool can be used to constrain a corner of a square to the intersection of the axes?

☐	☐	☐	☐
The Select tool	The Constrain coincident tool	The Extrude tool	The Pad tool

- What does the green color on a line indicate?

☐	☐	☐	☐
The line is selected	The line is pre-selected	The line is hidden	The line is locked

- Which technique is used to take a 2D shape, like a square, and give it depth by adding thickness to it?

☐	☐	☐	☐
Extrusion	Constraining	Padding	Rotation

4 Explain the difference between the "Constrain coincident" and "Constrain point onto object" tools.



- 5 Explain the purpose of the "Constrain horizontal distance" and "Constrain vertical distance" tools.

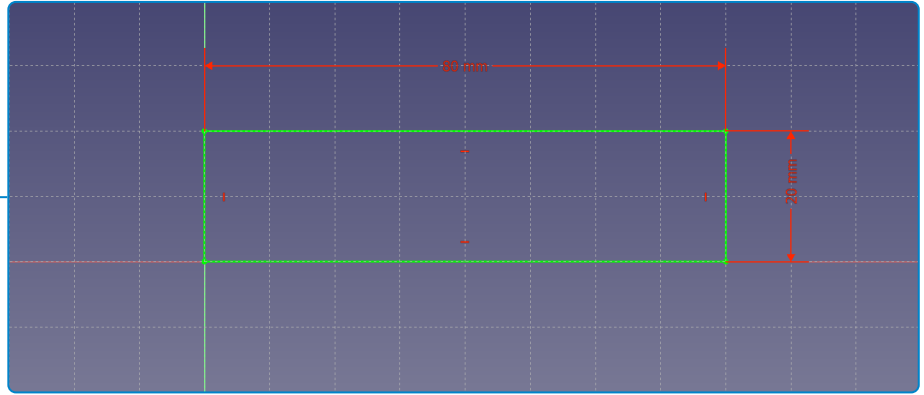
- 6 Describe the process of creating a 3D shape using the padding technique.

- 7 Use the Create line tool to create a line of unit length 100 and fully constrain it.

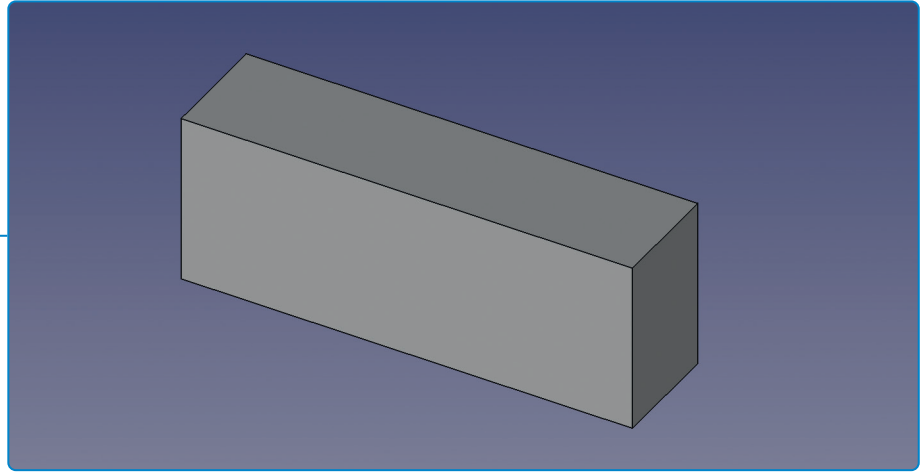


- 8 Create a fully constrained rectangle with long sides with lengths of 80 mm and short sides with lengths of 20 mm. Then use the Pad tool to pad the rectangle to have a height of 30 mm.

2D Sketch



3D Model





Introduction to Gears

A gear is a toothed wheel that connects with another similar gear, usually larger or smaller. Gears are an important part of mechanical systems and have been used for centuries to transmit power and motion. Gears work together to transfer rotational motion from one gear to another. The design of gears determines the type of motion that can be transmitted, the speed of movement, and the torque that can be sent. Gears come in various shapes and sizes, including spur gears, helical gears, bevel gears, and worm gears. In this lesson, we will focus on the most common type of gear, the involute-based spur gear.

A gear can be used to change speed, direction, or torque. Increasing the torque in a machine (such as a bike or a car) results in lower speeds, while less torque leads to higher speeds without the need for more engine power. This is due to the following law:

$$\text{Power (watt)} = \text{Torque (Nm)} \times \text{Angular Velocity (rad/s)}$$



$$\text{Torque (Nm)} = \frac{\text{Power (watt)}}{\text{Angular Velocity (rad/s)}}$$

Here are some key things to remember about gears:

- You can measure a gear by counting its teeth.
- We combine gears according to radius and thickness.
- Gears have a cross hole in the center so they can be placed on axles and transfer rotation from one axis to another.
- The drive gear (blue in the diagram) is usually connected to a motion source (e.g., a motor).
- The driven gear (white in the diagram) moves based on the movements of the drive gear and is often connected to the part of the machine that does the machine's work (a drill head, a circular saw, or the wheel of a bicycle).

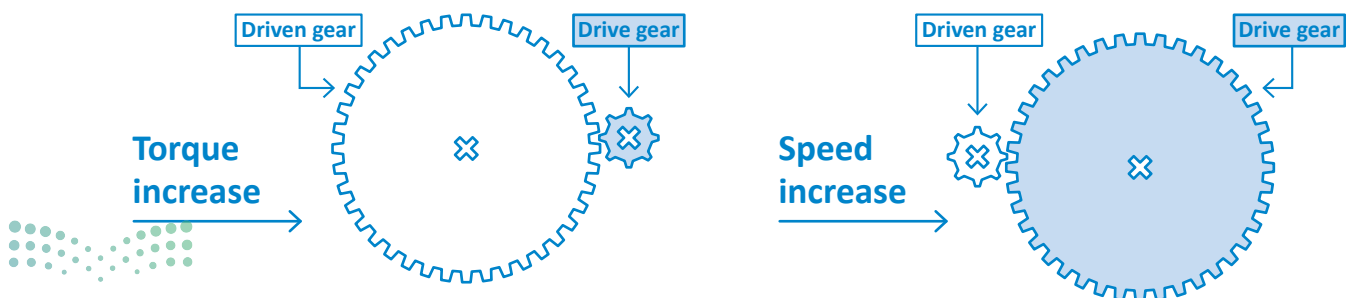


Figure 2.40: Torque increase vs. Speed increase

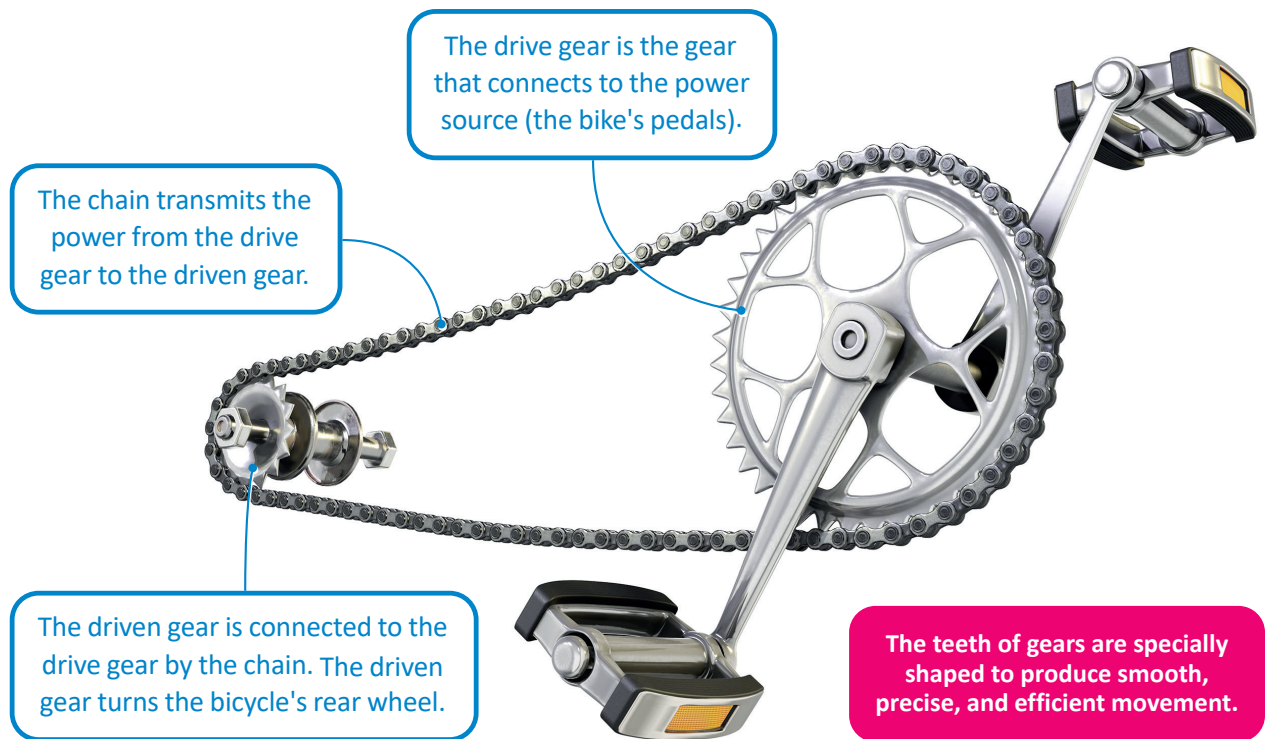


Figure 2.41: Mechanism of a bicycle

Creating a Simple Machine

In this lesson, you will learn how to design and create a simple two-gear cylinder base. On the base, you will place two involute-based spur gears, each with a different number of teeth, to create a simple mechanism. After you have completed the models, you will export their designs for 3D printing.

When two gears are connected, the number of teeth on each gear determines how fast they rotate and how much force they have. If a small gear with 8 teeth is connected to a big gear with 24 teeth, the big gear will rotate once for every 3 rotations of the small gear. This makes the big gear produce greater torque, so it can push or lift heavier things than the small gear by itself.

$$\text{Gear Ratio} = \frac{T_1}{T_2}$$

T1 is the number of teeth (8) on the first gear.

T2 is the number of teeth (24) on the second gear.

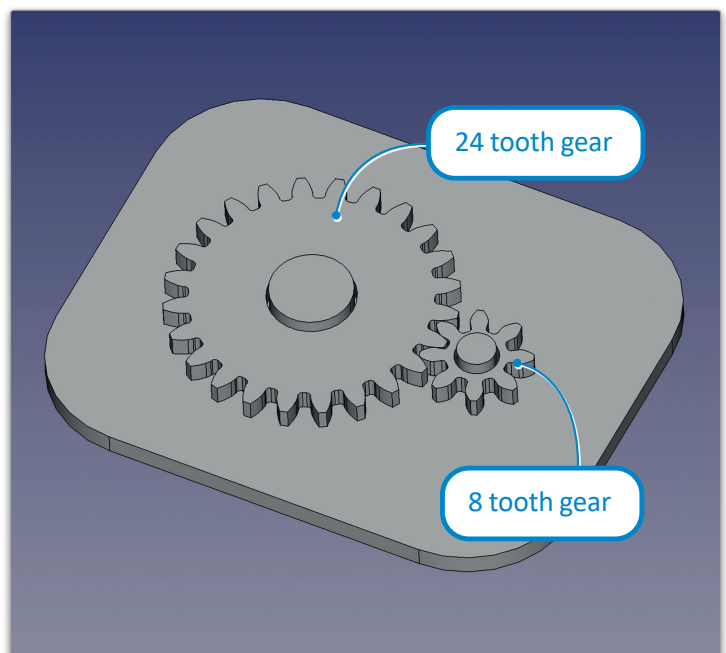
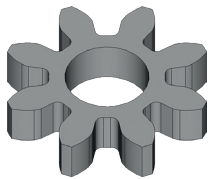


Figure 2.42: 3D design of a simple machine

Designing an 8-Tooth Gear

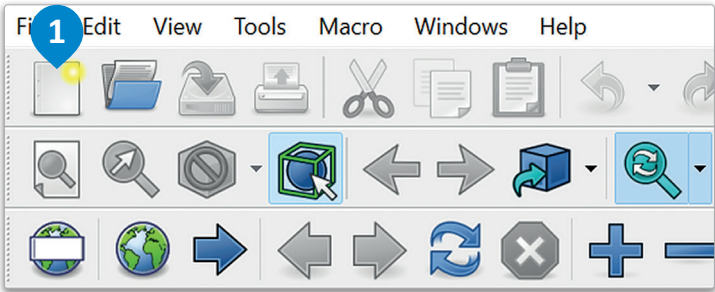
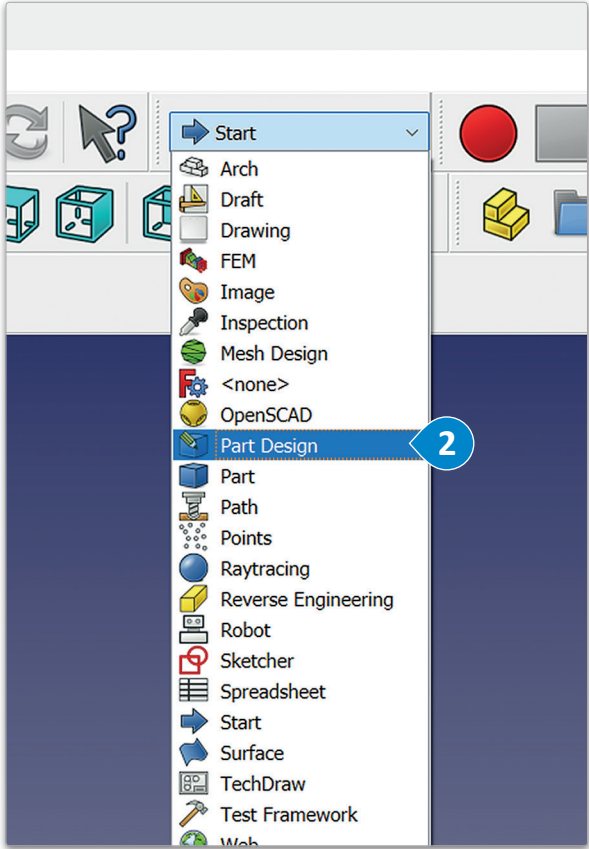
You will begin by designing an 8-tooth gear for your project. This gear will serve as one of the components of our two-gear cylinder base. Using the involute gear feature in FreeCAD, you can quickly and easily create a gear with accurate and precise teeth. This will help you to ensure a smooth and efficient operation when connecting the two gears together.



Let's get started by creating a new document.

The involute gear is a type of gear that has an involute-shaped tooth profile. This tooth profile is designed to reduce stress and wear, making it ideal for applications requiring high torque and precise motion control. Involute gears are widely used in various applications, including power transmission systems, machine tools, and automotive systems.

- To create a new document:
- > Click on the icon "New", from the **toolbar**. **1**
 - > From the **workbench drop-down menu**, select the "Part Design" workbench. **2**



When you change the workbench, the menu bar changes to reflect the tools and features that are available in the selected workbench.

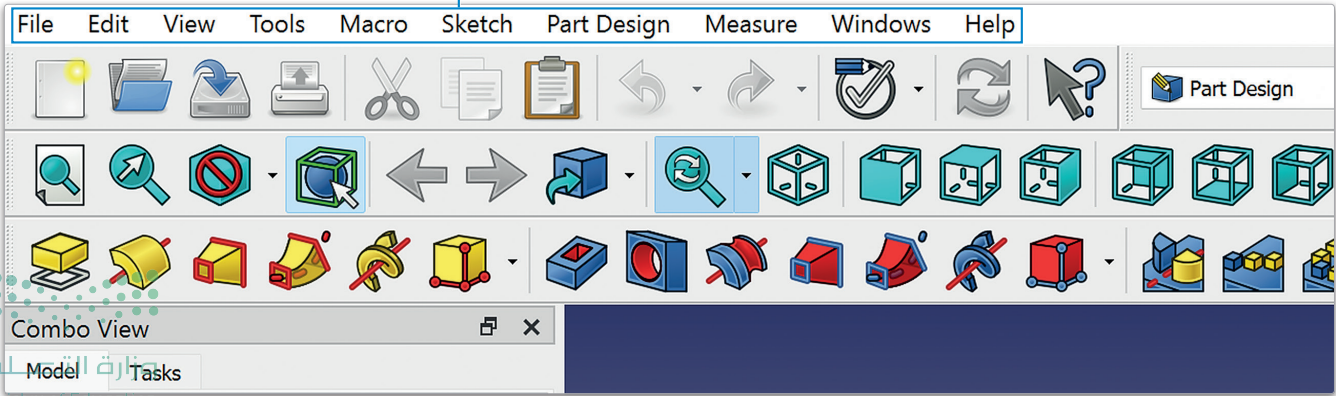


Figure 2.43: Creating a new document

To design a gear in FreeCAD, you first need to create a solid body by using solid modeling tools like the Part Design or the Part workbench. To create a body for the 8-tooth gear you will use the Create body tool from the Part Design workbench.

To create an 8-tooth gear body:

- > From the **toolbar**, click the **Create body** tool. **1**
- > From the **Data** tab, change the **Label** to **Small Gear**. **2**

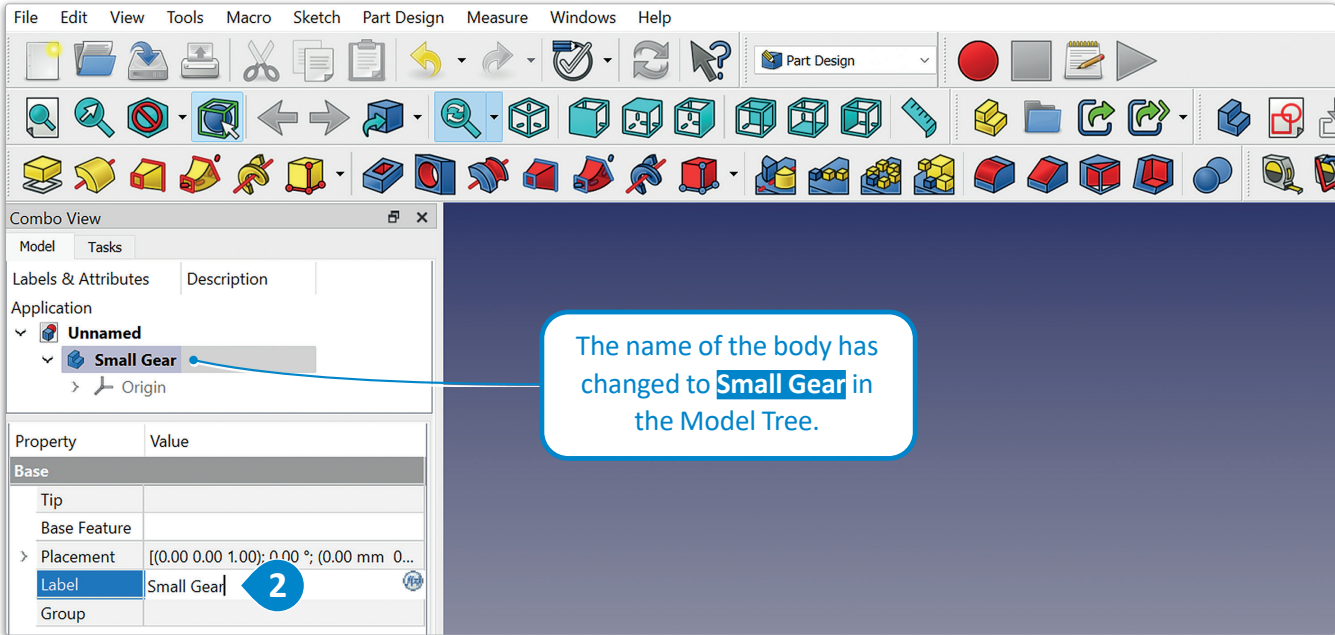
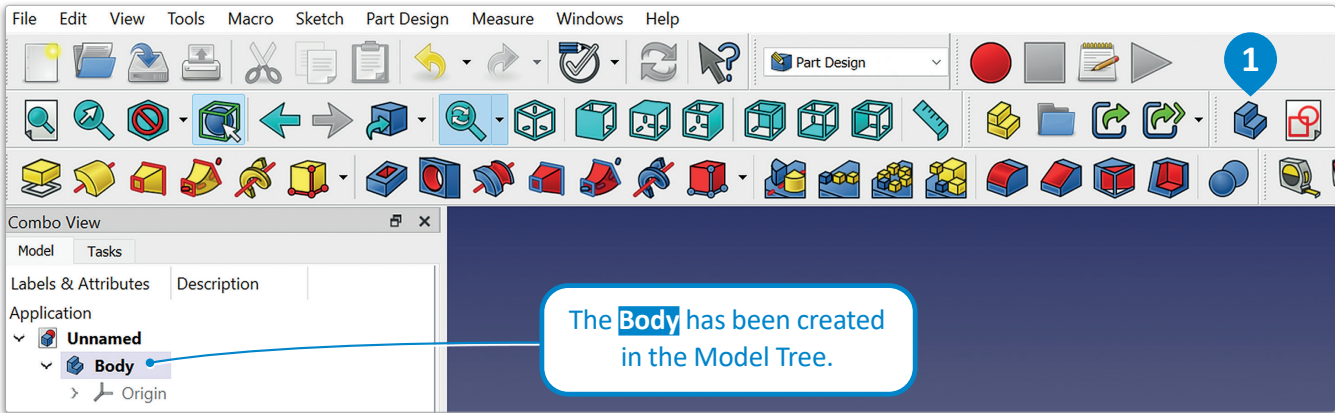


Figure 2.44: Creating an 8-tooth gear body

INFORMATION

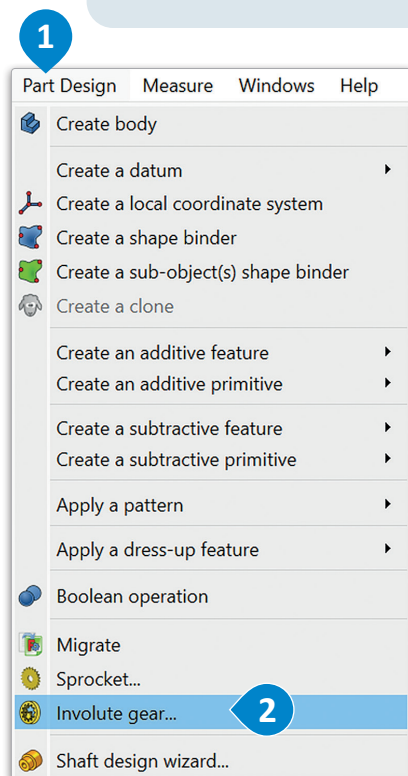
When you have multiple bodies in a design, it can be difficult to keep track of which body represents what part of the project. Labeling the bodies with descriptive names makes it easier to identify and manage each body.

Now that you have created the solid body, you can use the Involute gear tool. The Involute gear tool is a macro included in the FreeCAD installation, and allows you to specify the number of teeth, the module, the pressure angle, and other gear parameters. By entering these parameters and clicking OK, you can generate an involute gear suited to your needs.

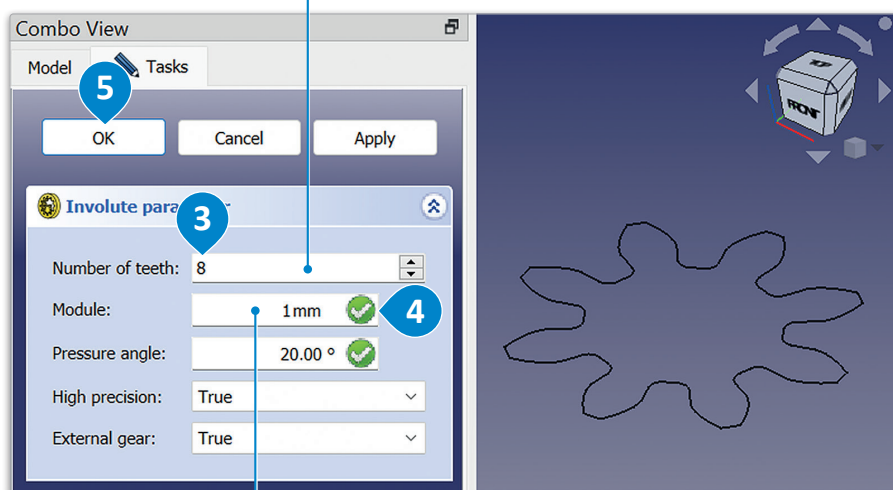
To add an involute gear:

- > From the **Menu** menu, click **Part Design** ¹ and select **Involute gear....** ²
- > Change **Number of teeth** to **8**. ³
- > Change **Module** to **1 mm** ⁴ and click **OK**. ⁵

A macro is a script or program that automates a series of tasks or commands in the software. The Involute gear tool is a macro that provides a convenient way to generate an involute gear without having to perform the complex geometry calculations and operations manually.



This specifies the **Number of teeth** the gear will have.



The **Module** parameter affects the distance between two adjacent gear teeth and is used to specify the size of the gear.

The generated gear will be a solid 3D model that you can then modify and manipulate further.

An **InvoluteGear** has been created in the Model Tree.

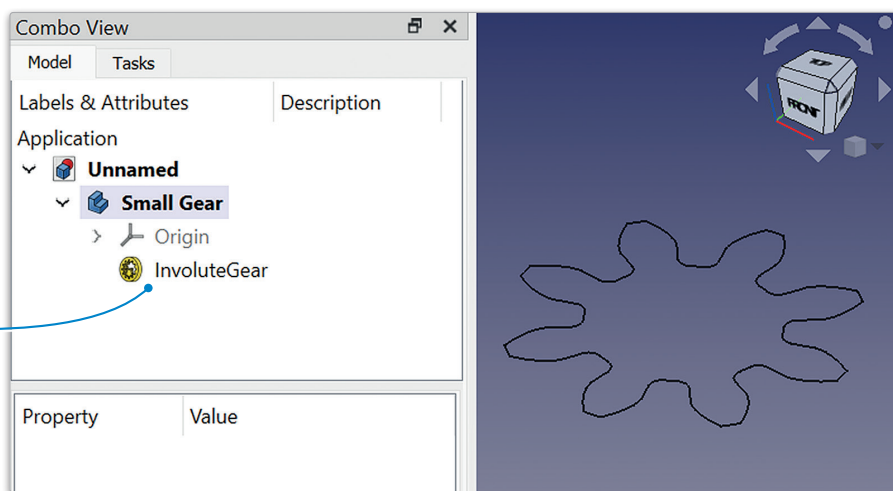


Figure 2.45: Adding an involute gear

Now that you have entered all the required parameters and the 8-tooth gear is generated as a 2D object, it's time to use the Pad tool to change it into a 3D gear.

To make the gear 3D:

- > From the **Combo View**, click the **Model** tab. **1**
- > From the **Model** tab, select **InvoluteGear**. **2**
- > From the **toolbar**, select the **Pad** tool. **3**
- > From the **Tasks** tab, change the length to **2 mm**, **4** and click **OK**. **5**

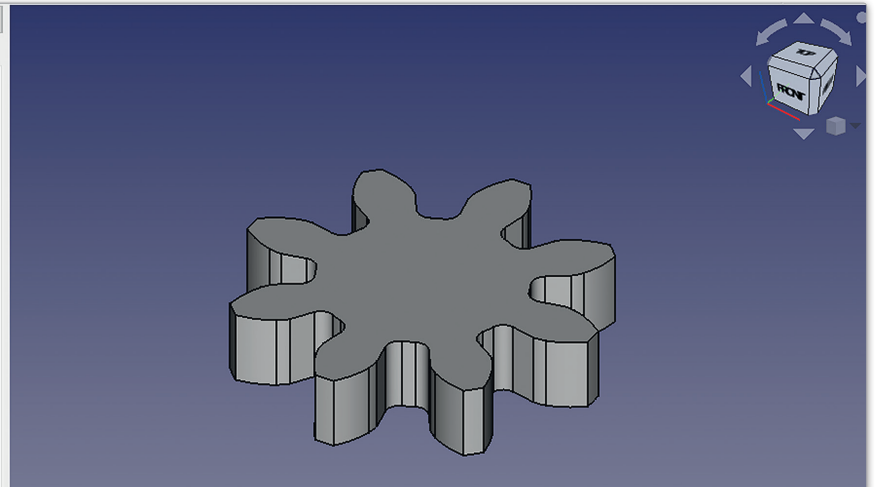
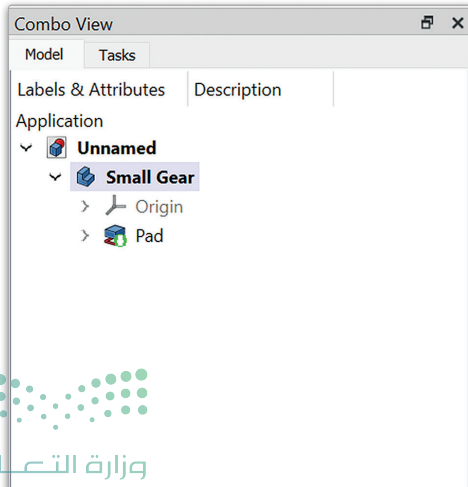
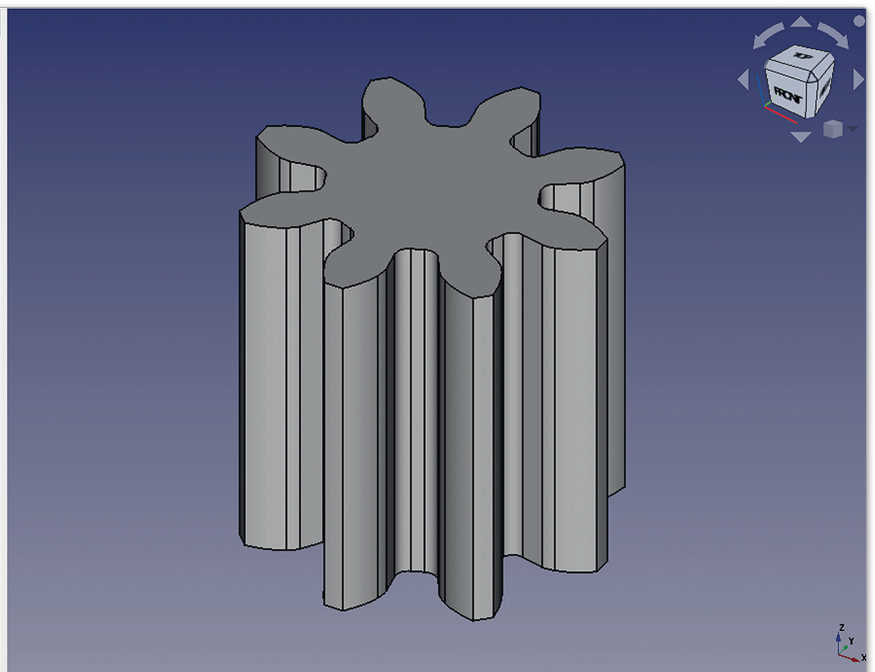
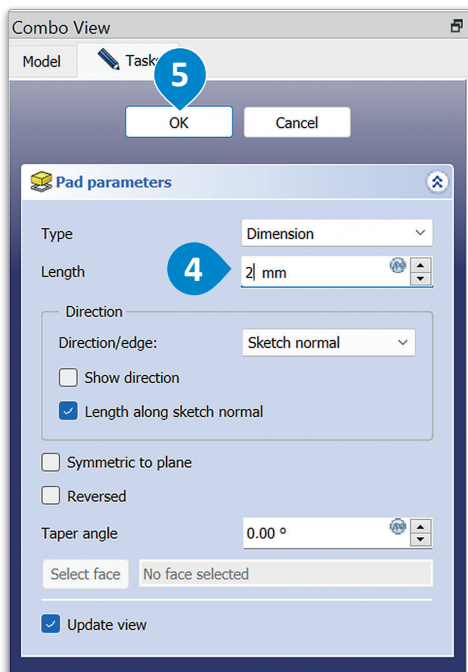
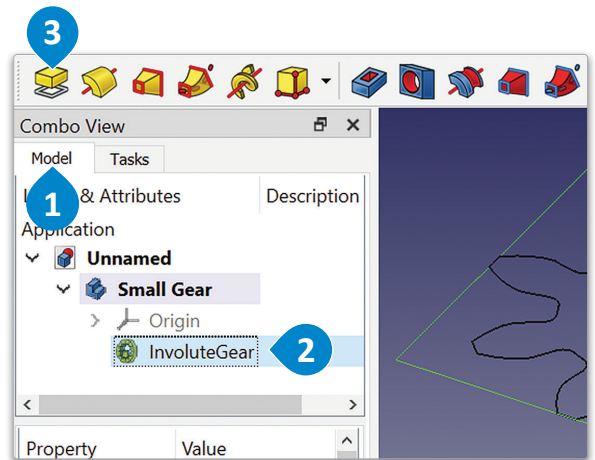
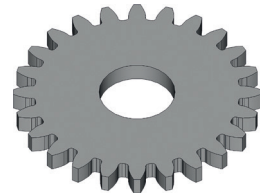


Figure 2.46: Making the gear 3D

Designing a 24-Tooth Gear

Now let's create a second body that you will use to make the 24-tooth gear.



To create a 24-tooth gear body:

- > From the **toolbar**, click the **Create body** tool. **1**
- > From the **Data** tab, change the **Label** to **Big Gear**. **2**

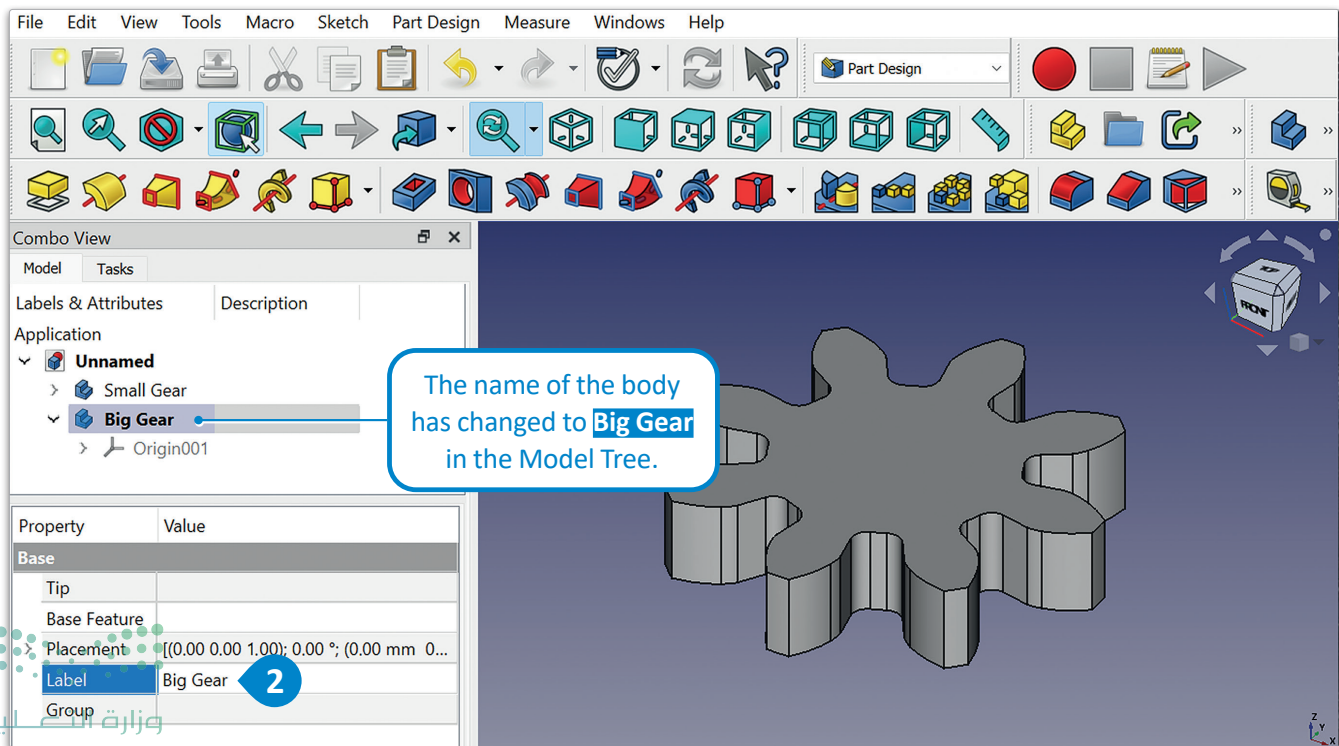
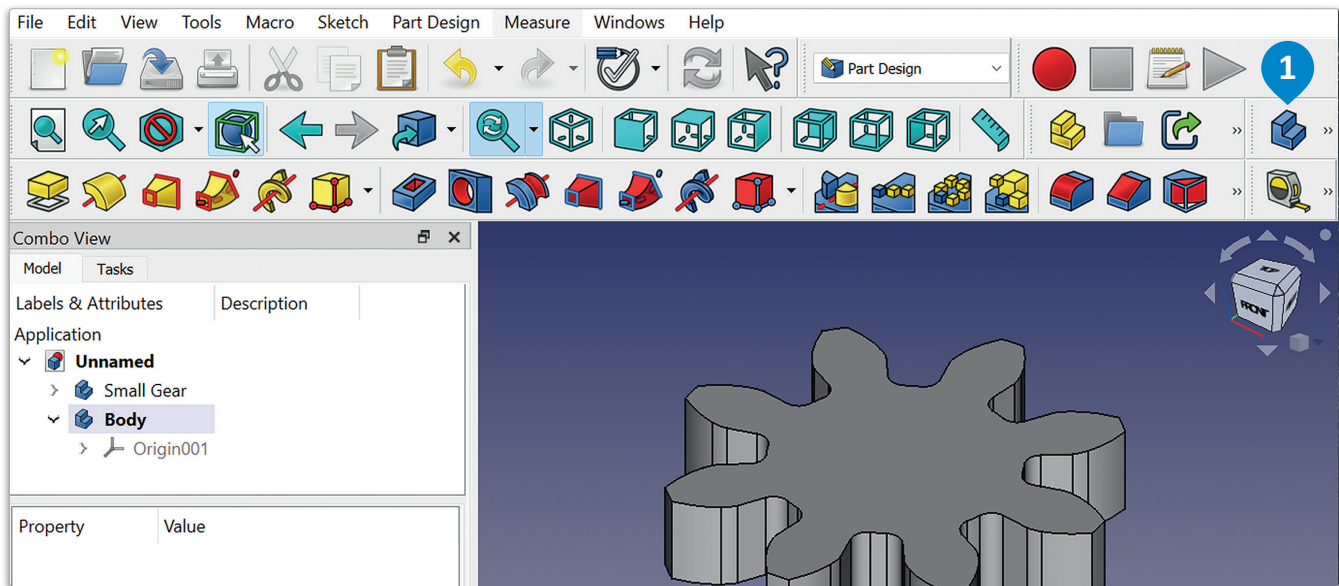


Figure 2.47: Creating a 24-tooth gear body

Now that you have created the solid body, use the Involute gear tool to create the 24-tooth gear.

To add an involute gear:

- > From the **Menu menu**, click **Part Design** **1** and select **Involute gear...** **2**
- > Change **Number of teeth** to **24**. **3**
- > Change **Module** to **1 mm** **4** and click **OK**. **5**
- > From the **Combo View**, click the **Model** tab. **6**
- > From the **Model** tab, select **InvoluteGear**. **7**

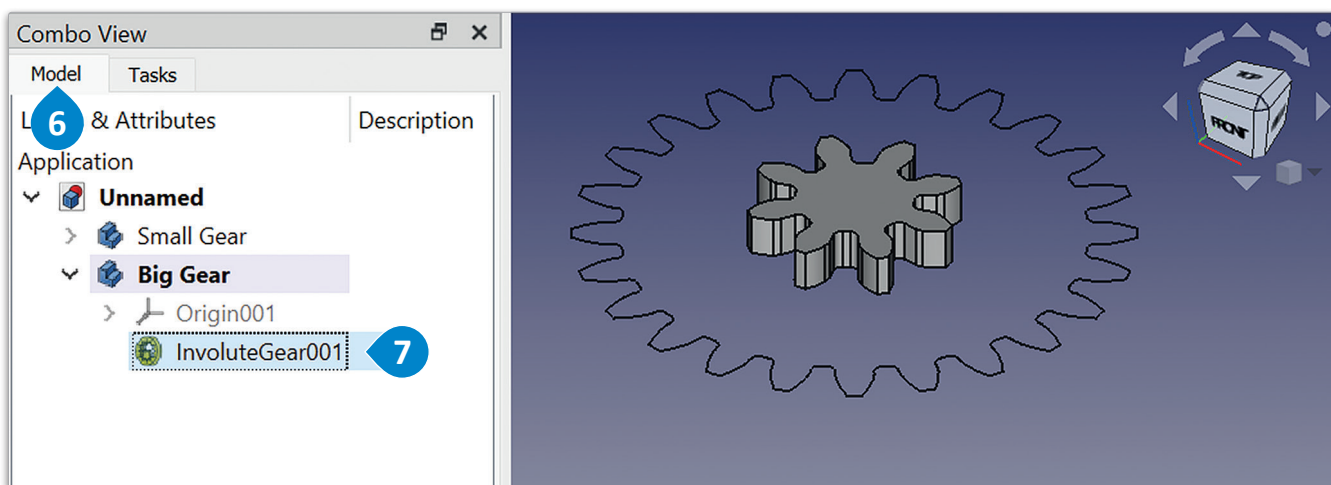
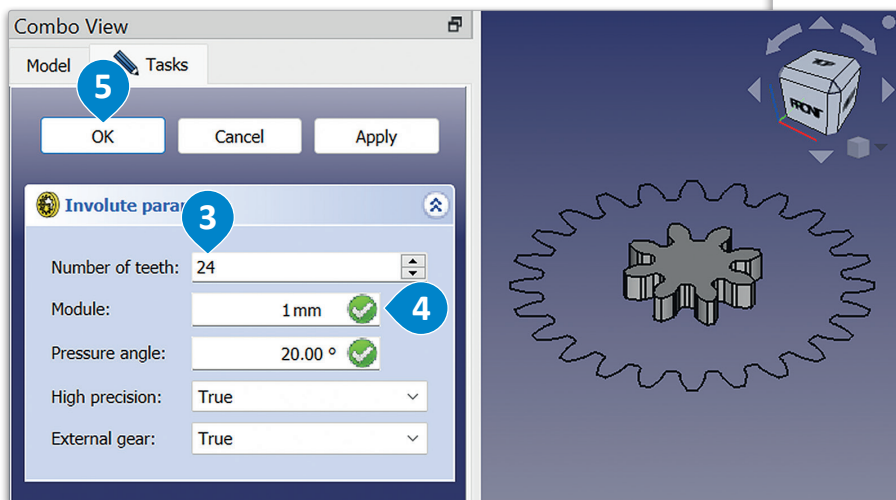
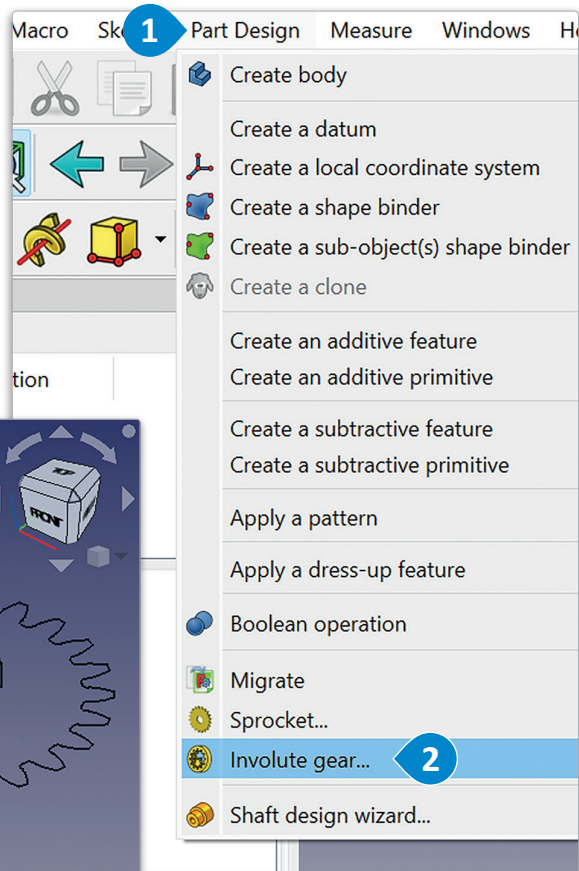


Figure 2.48: Adding an involute gear

INFORMATION

Setting the module to 1.00 mm means that the gear teeth will be 1.00 mm wide and 1.00 mm high, which is a common size for small gears used in various applications.

Now that you have entered all the required parameters and the 24-tooth gear has been generated, let's use the Pad tool to change it into a 3D gear.

To make the gear 3D:

- > From the **toolbar**, select the **Pad** tool. **1**
- > From the **Tasks** tab, change the length to **2 mm**, **2** and click **OK**. **3**

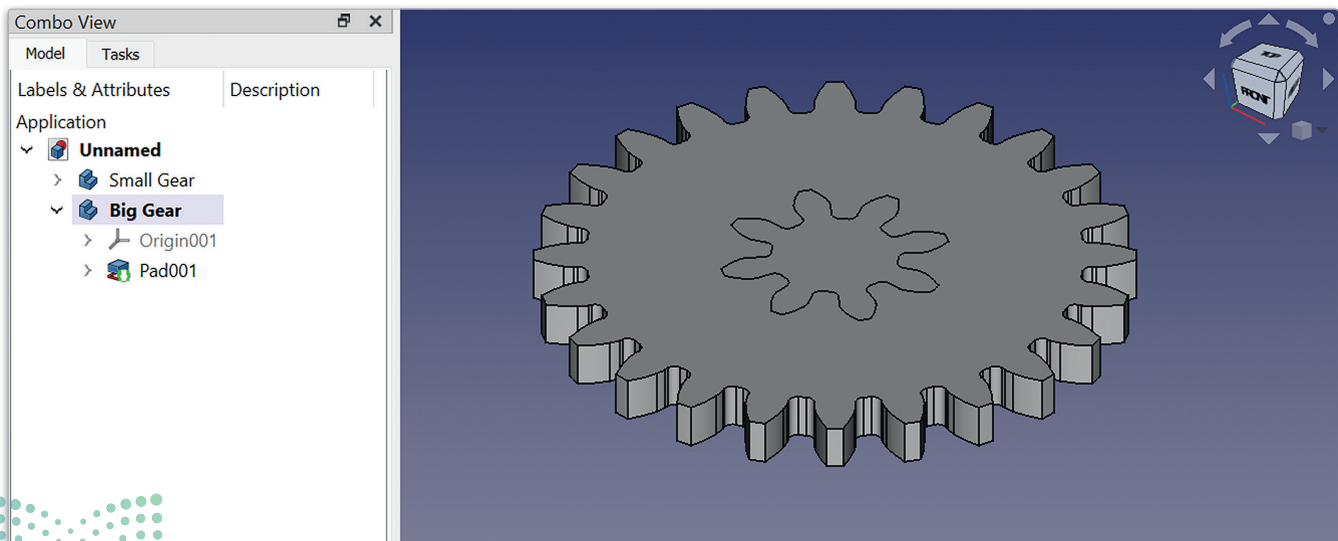
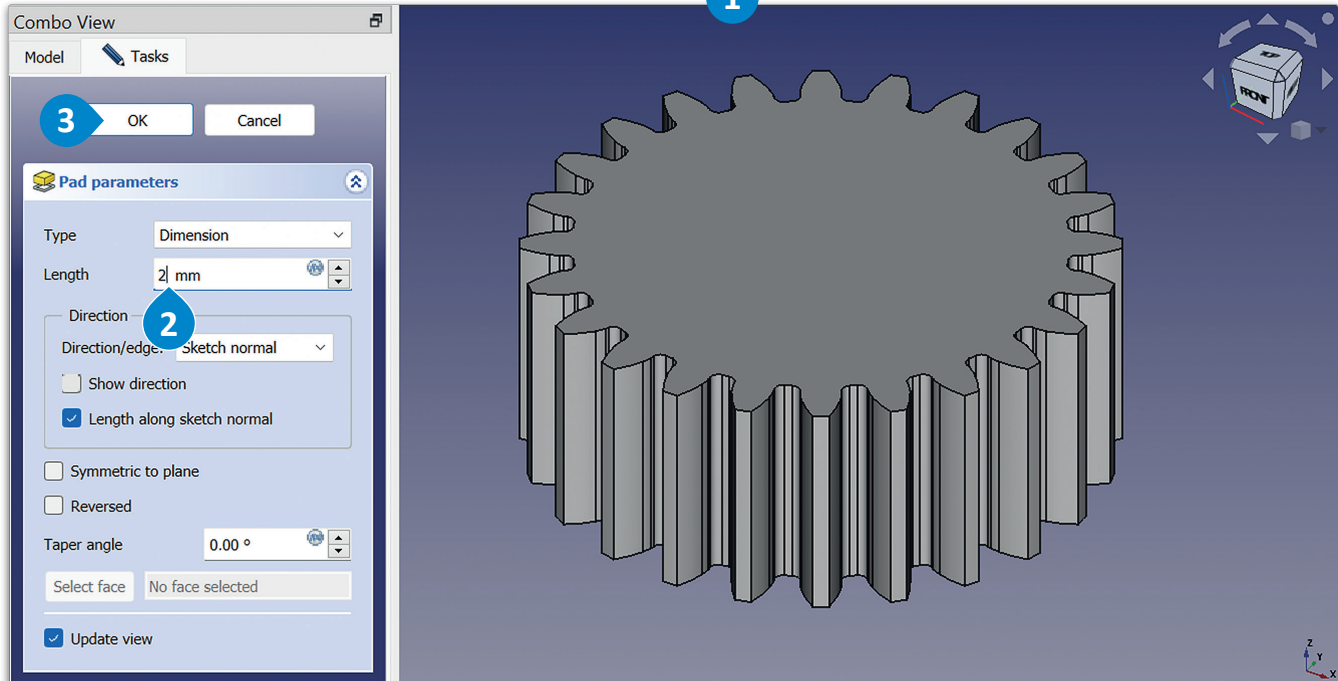
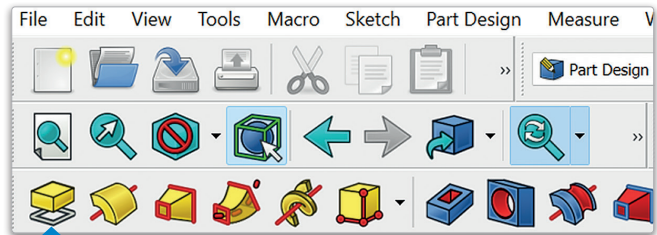


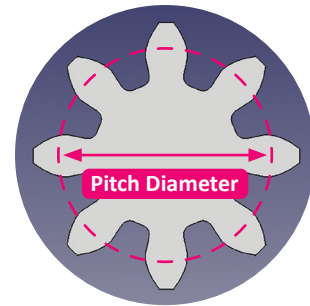
Figure 2.49: Making the gear 3D

Gears Engagement

When you use gears, it's essential to determine the center distance between them in order to ensure proper meshing and engagement of the gears. To determine the center distance between the two gears of your project, you can use the following formula:

$$\text{Distance} = \frac{(\text{Module} * (T1 + T2))}{2}$$

By using this formula you ensure that the gears will turn smoothly and without excessive wear or vibration.



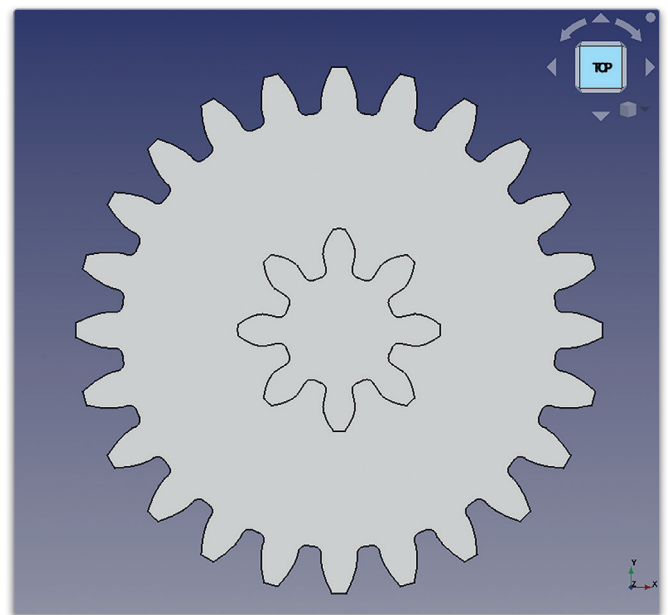
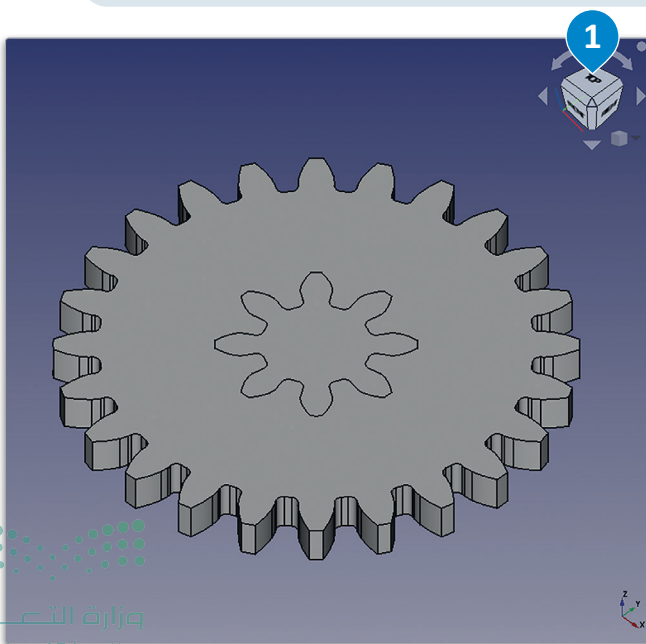
Module is the pitch diameter divided by the number of teeth.

"T1" and **"T2"** are the number of teeth on the Big and Small gears.

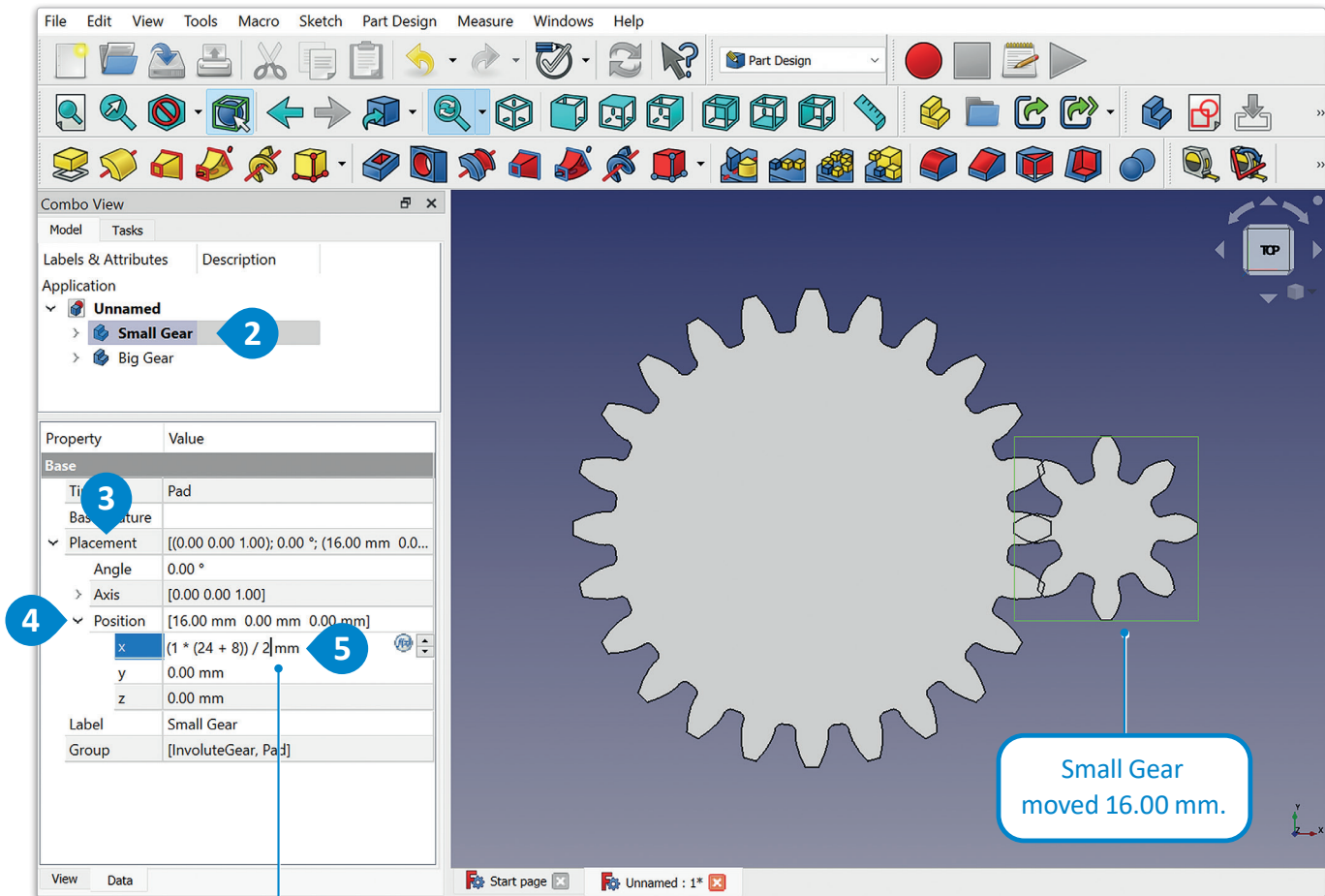
Now you will use the formula " $\text{Distance} = (\text{Module} * (T1 + T2)) / 2$ " to move the 8-tooth gear to ensure that the gears mesh properly and function as intended.

To move the Small Gear:

- > From the **Navigation Cube** click the **TOP** view. **1**
- > From the **Model Tree** select **Small Gear**. **2**
- > From the **Data** tab click **Placement**. **3**
- > From the **Placement** drop-down menu click **Position**. **4**
- > In the **x** box in the **Position** drop-down menu type $(1 * (24 + 8)) / 2$. **5**



The center distance is the distance between the center points of two gears, and it must be precise for the gears to mesh correctly and transfer power efficiently.



The center distance is defined in the x direction, so the formula should be applied to the x position in the Data tab.

Placement	[(0.00 0.00 1.00); 0.00 °; (16.00 mm 0.0...
Angle	0.00 °
Axis	[0.00 0.00 1.00]
Position	[16.00 mm 0.00 mm 0.00 mm]
x	16.00 mm
y	0.00 mm
z	0.00 mm
Label	Small Gear
Group	[InvoluteGear, Pad]

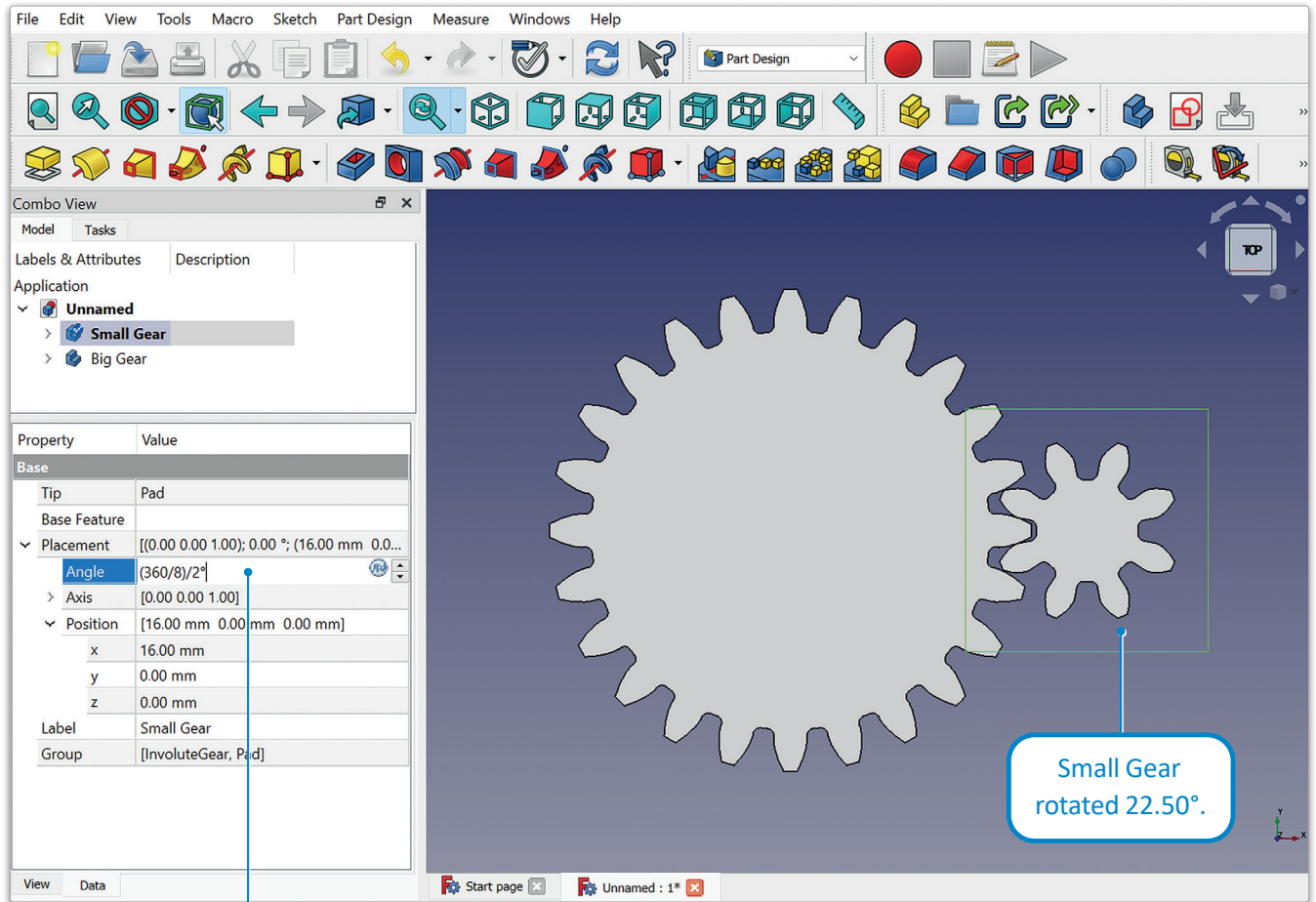
Figure 2.50: Moving the small Gear

INFORMATION

If the center distance between two gears is incorrect, the gears will not mesh properly and will not transfer power efficiently, resulting in misalignment, noise, and decreased performance.

You will then rotate the small gear to place it in the correct orientation for meshing. You will use the following formula to find the rotation angle in degrees:

$$\text{Rotation angle} = \frac{(360^\circ / \text{number of teeth})}{2^\circ}$$



Use the formula $(360/8)/2$ to rotate the small gear.

Placement	[(0.00 0.00 1.00); 22.50 °; (16.00 mm 0.00 mm 0.00 mm)]
Angle	22.50 °
Axis	[0.00 0.00 1.00]
Position	[16.00 mm 0.00 mm 0.00 mm]
x	16.00 mm
y	0.00 mm
z	0.00 mm
Label	Small Gear
Group	[InvoluteGear, Pad]

Figure 2.51: Rotating the small Gear



Making Holes in the Gears

Making a Hole in the Small Gear

Now that you have created and set the position of the two gears, it's time to open two holes, one for each gear, in order to attach them to a base. Let's start with the Small Gear.

To create a sketch in the top surface of the Small Gear:

- > From the **Model** tab, double click to select the **Small Gear**. **1**
- > Click the **Small Gear** to select its top surface. **2**
- > From the **toolbar**, click the **Create sketch** tool. **3**

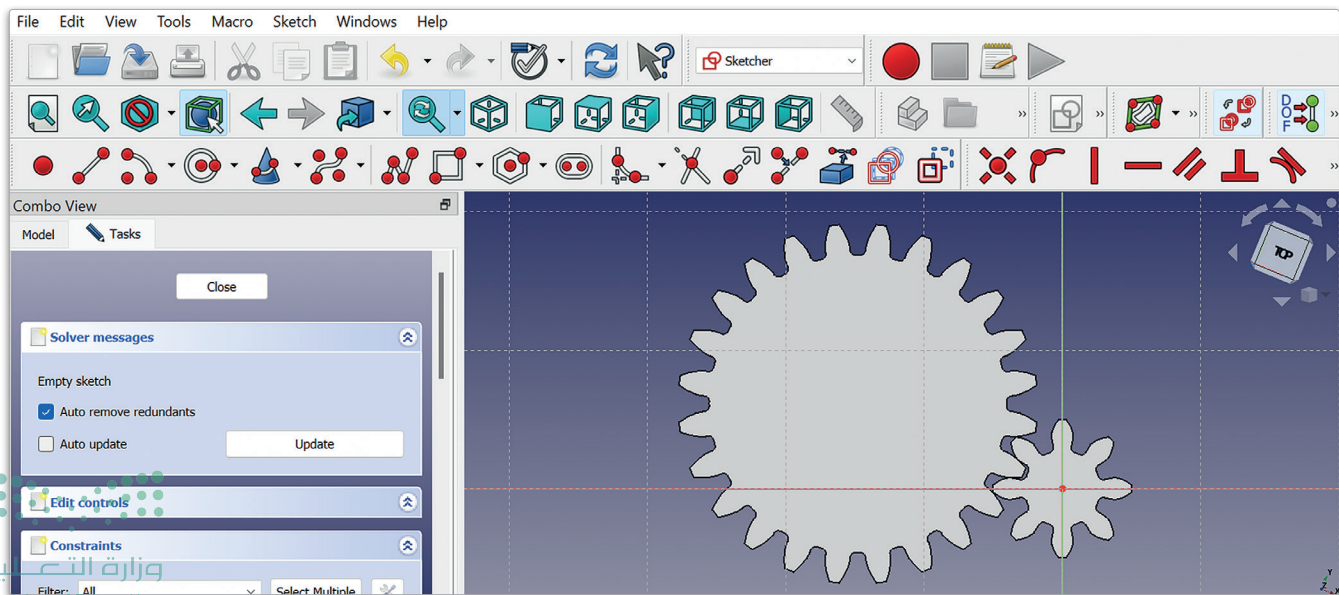
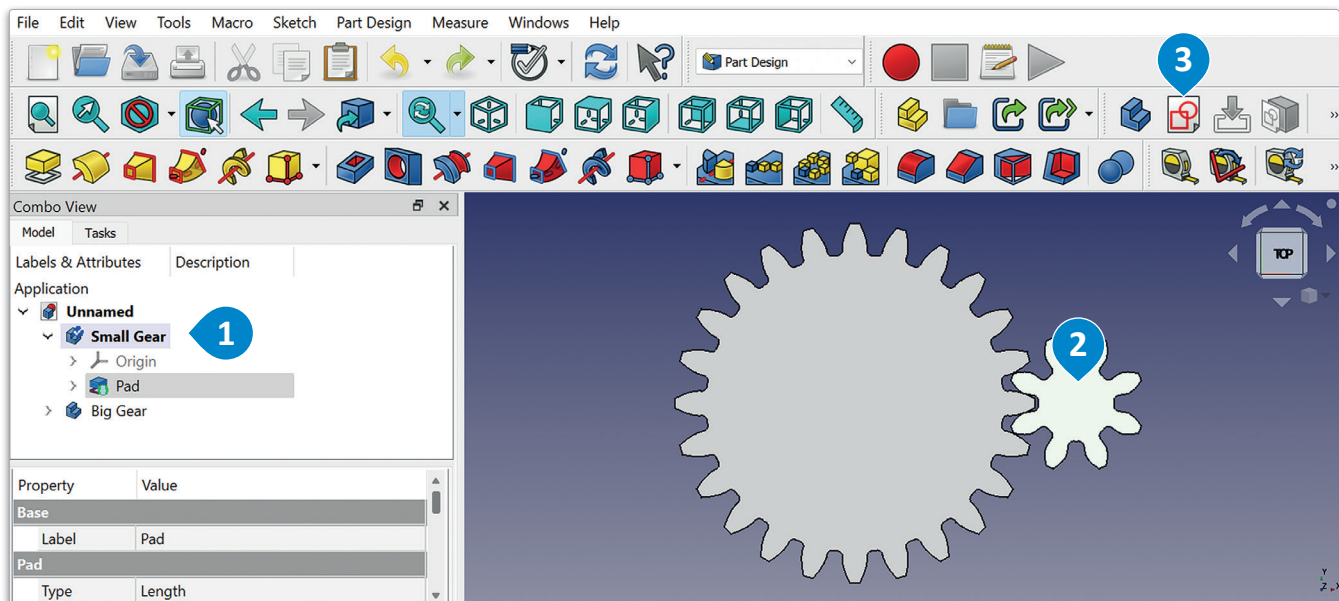


Figure 2.52: Creating a sketch in the top surface of the Small Gear

To create a hole in the Small Gear, you must specify where and how large this hole should be. You will start by using the Create circle tool to create a circle. Then you will use the Constrain radius tool to set the circle's radius.

To create a circle:

- > From the **toolbar**, select the **Create circle** tool, **1** select the center of the gear **2** then drag the mouse/cursor away from the center of the gear and click to create the circle. **3**
- > From the **toolbar**, click on the arrow symbol, **4** select the **Constrain radius** tool **5** and select the circle. **6**
- > In the **Insert radius** window, type **2 mm** **7** and click **OK**. **8**

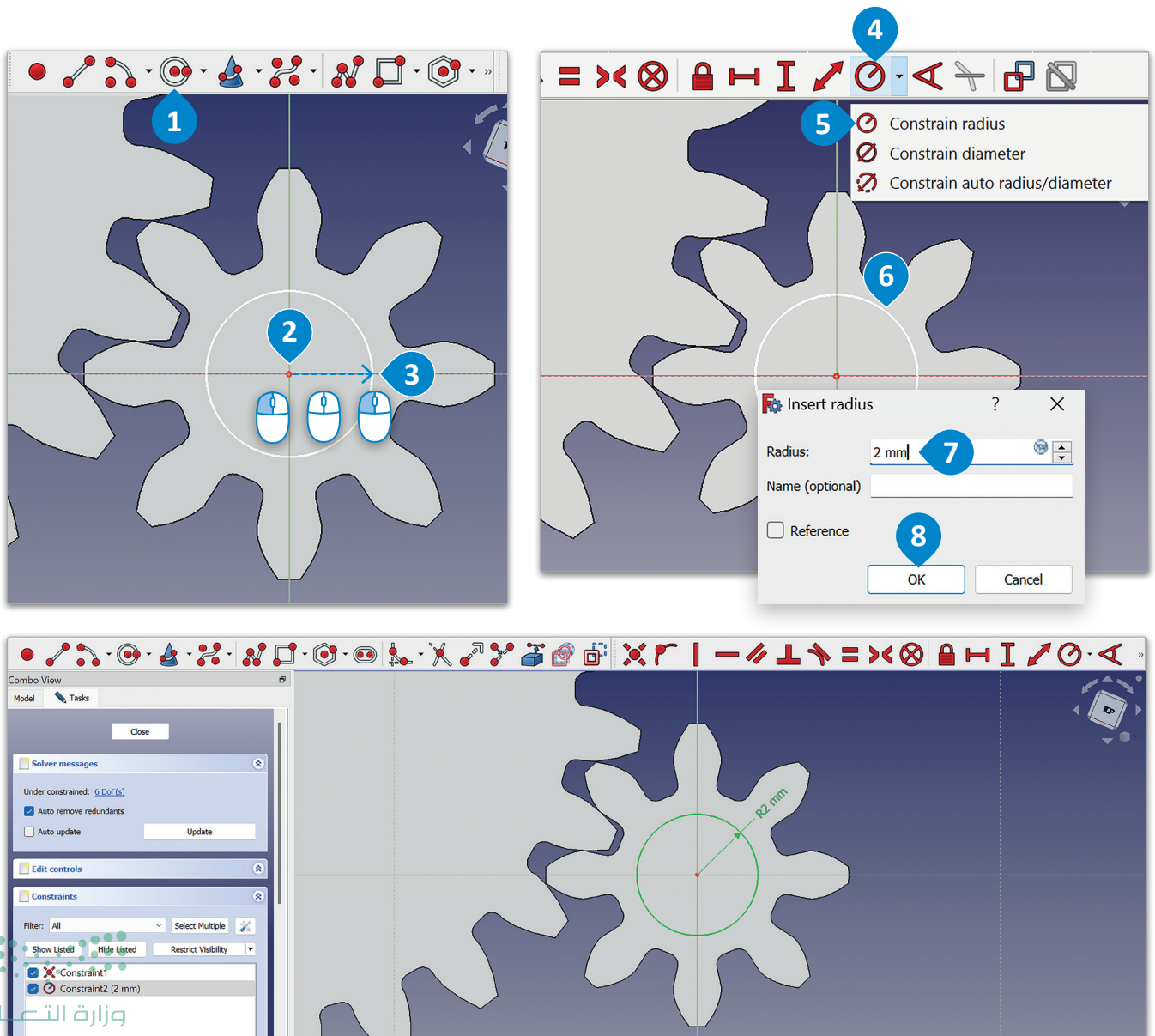
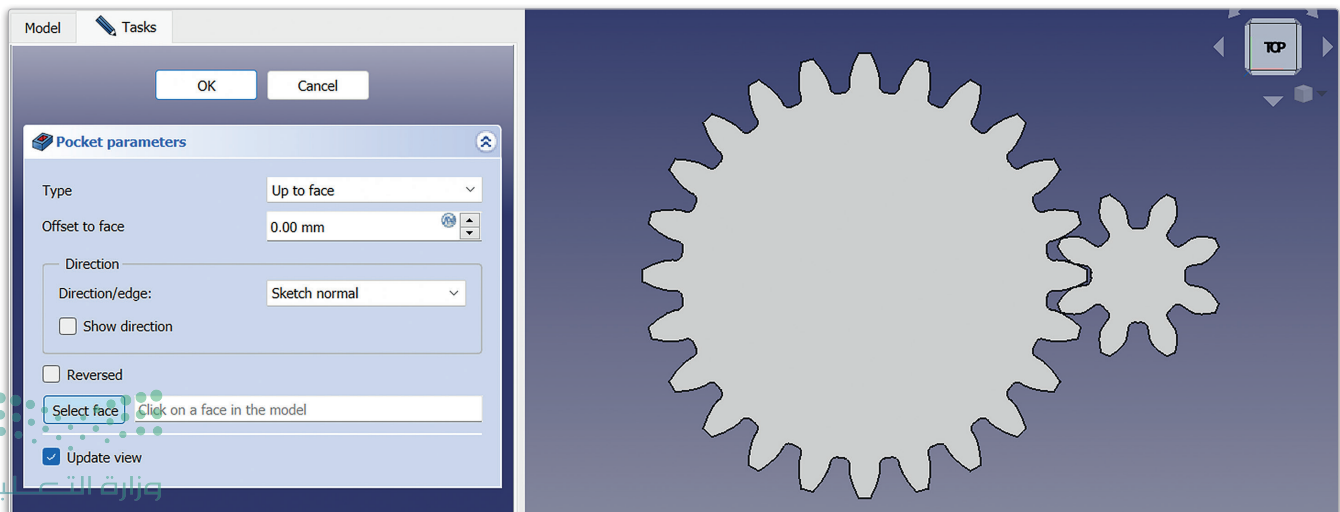
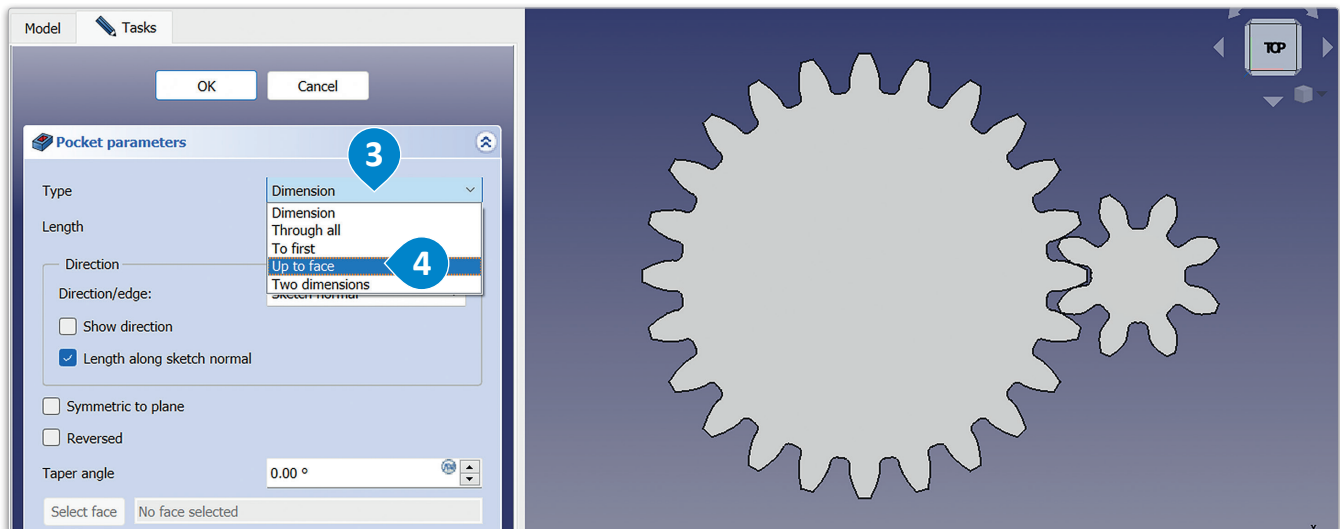
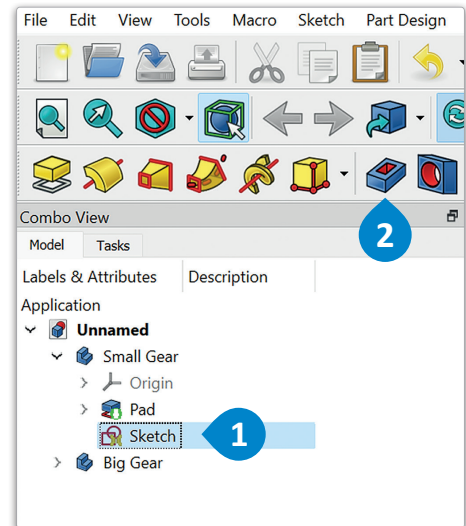


Figure 2.53: Creating a circle

Now you will use the Pocket tool that allows you to create a hole or cavity in a body.

To create a hole:

- > From the **Model Tree**, select **Sketch**. **1**
- > From the **toolbar**, select the **Pocket** tool. **2**
- > In the **Pocket parameters** window, click the drop-down menu, **3** and select **Up to face**. **4**
- > Hold down the scroll wheel and move the mouse to bring the small gear to the center of the screen. **5**
- > Hold down the **⇧ Shift** key, click the right mouse button and drag to show the bottom of the gear. **6**
- > Click the bottom side of the small gear to make the hole, **7** and click **OK**. **8**



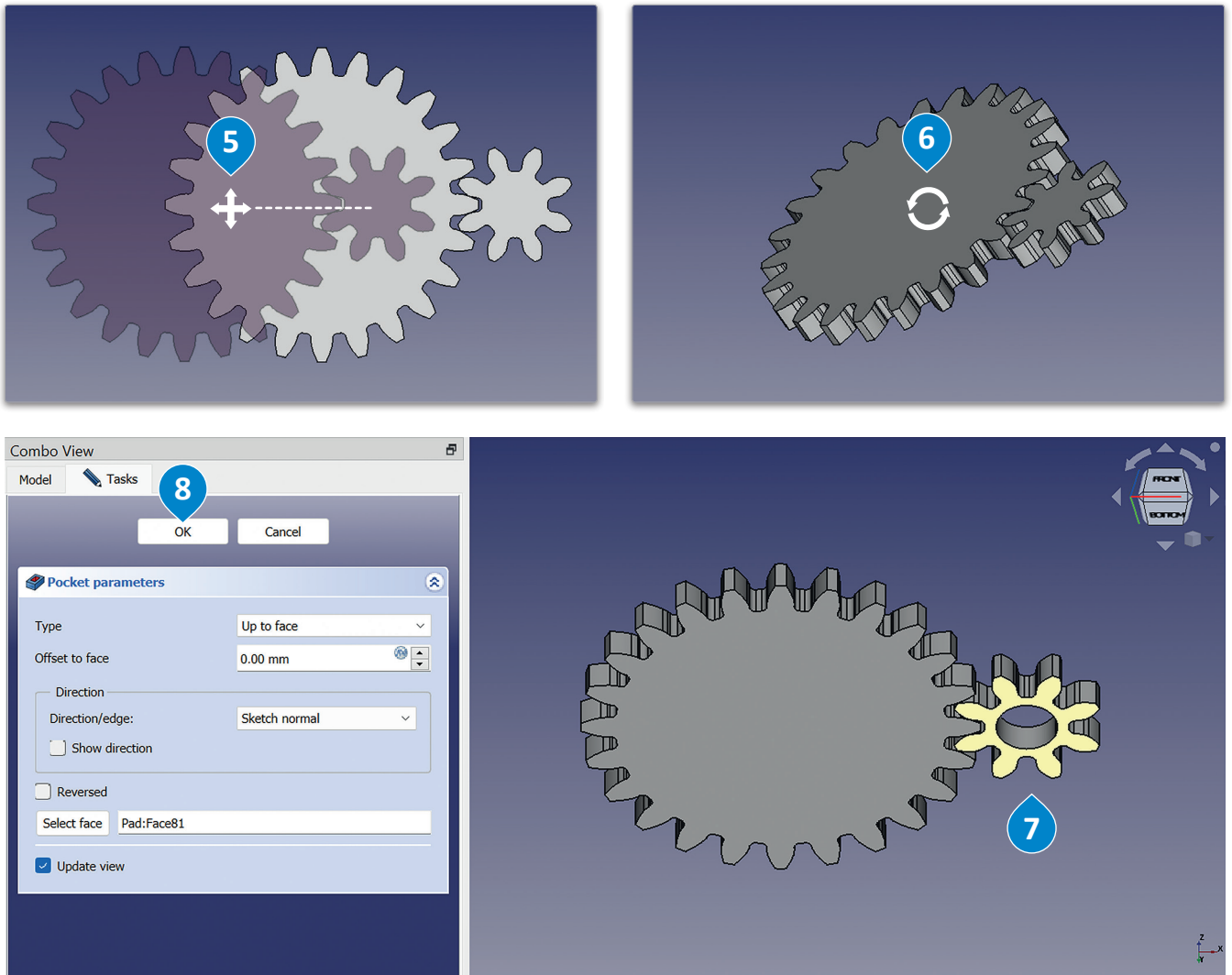


Figure 2.54: Creating a hole

Table 2.7: View options

Icon	Description
	To pan the view, you can hold down the middle mouse button (scroll wheel) and move the mouse.
	To rotate the view, you can hold down the Shift key and click and drag the right mouse button.

By setting the pocket type to "Up to face," you are specifying that the pocket will go all the way through the body until it reaches the selected face. This is useful for creating holes in gears, as it allows you to connect them to other parts in the future.

INFORMATION

To zoom in and out, you can scroll the mouse wheel up and down, or use the zoom buttons on the toolbar.

Making a Hole in the Big Gear

Now that you have finished with the small gear, it's time to use the same method to make a hole in the Big Gear. This time the hole will be larger.

To create a sketch on the top surface of the Big Gear:

- > Use the **Navigation Cube** to rotate the models to **TOP view**. **1**
- > From the **Model** tab, double click to select the **Big Gear**. **2**
- > Click the **Big Gear** to select its top surface. **3**
- > From the **toolbar**, click the **Create sketch** tool. **4**

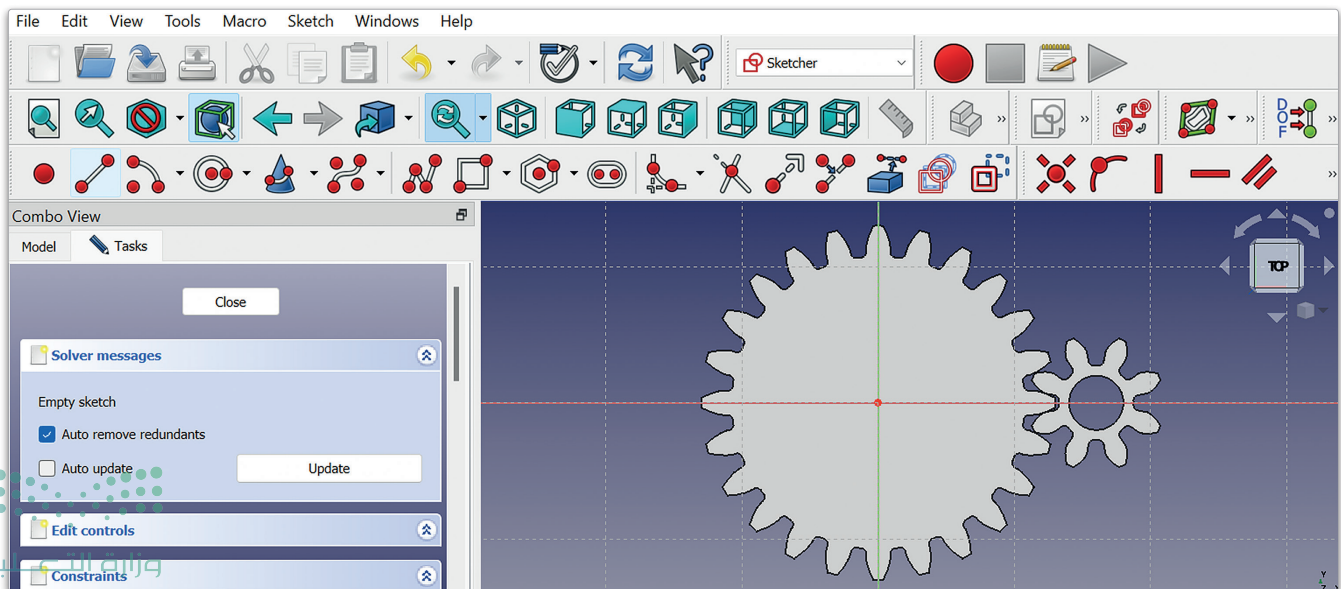
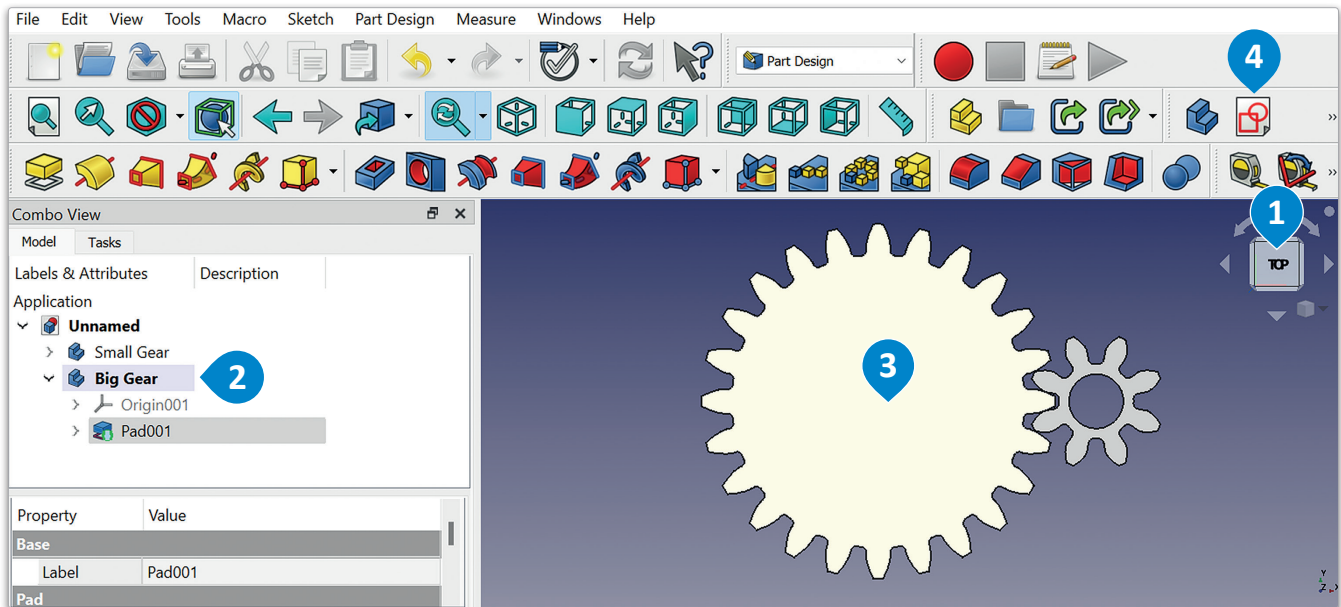


Figure 2.55: Creating a sketch on the top surface of the Big Gear

Use the Create circle tool to create a circle for the hole. Then you will use the Constrain radius tool to set the circle's radius. This time the radius will be 4 mm.

To create a circle:

- > From the **toolbar**, select the **Create circle** tool, **1** select the center of the axis **2** and click to create the circle. **3**
- > From the **toolbar**, select the **Constrain radius** tool, **4** and select the circle. **5**
- > In the **Insert radius** window, type **4 mm** **6** and click **OK**. **7**

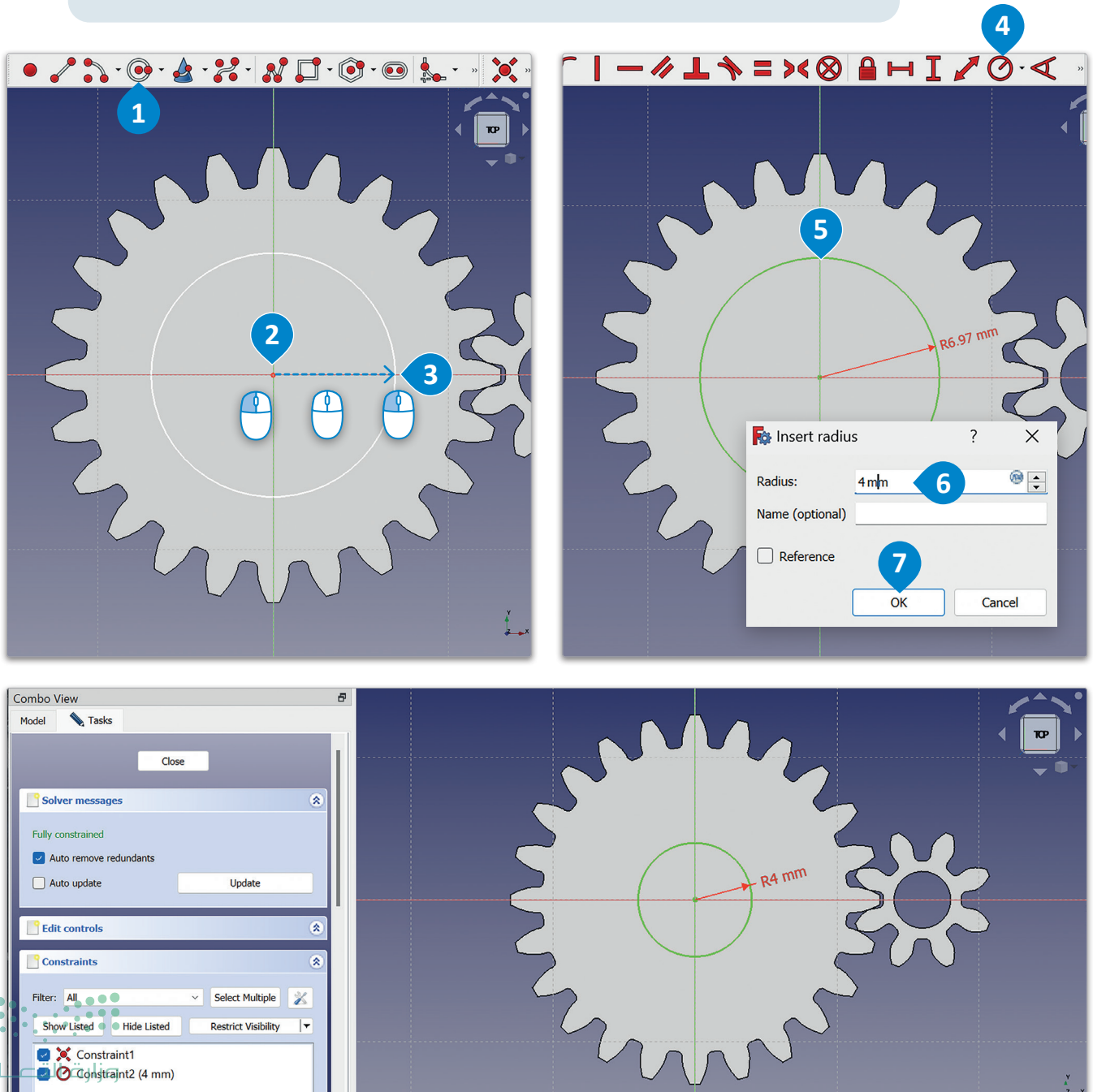


Figure 2.56: Creating a circle

Now that you have created the circle, use the Pocket tool to create a hole in the Big Gear.

To create a hole:

- > From the **Model Tree**, select **Sketch**. ①
- > From the **toolbar**, select the **Pocket** tool. ②
- > In the **Pocket parameters** window, click the drop-down menu, ③ and select **Up to face**. ④
- > Hold down the **⇧ Shift** key, click the right mouse button and drag to rotate to show the bottom of the gear. ⑤
- > Click the bottom side of the big gear to make the hole, ⑥ and click **OK**. ⑦

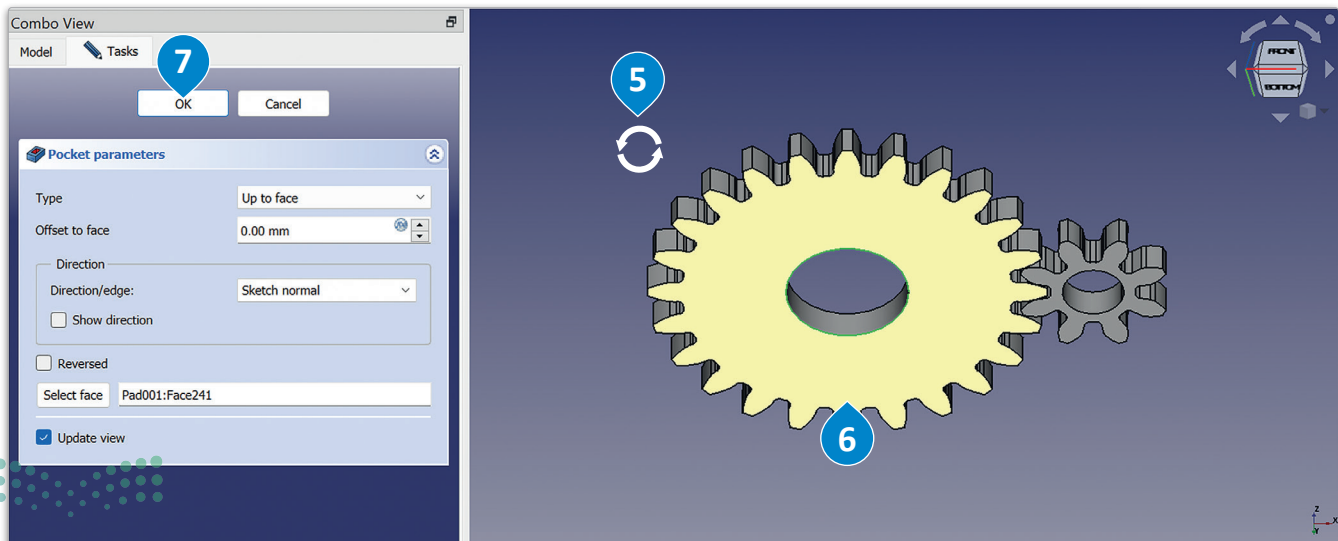
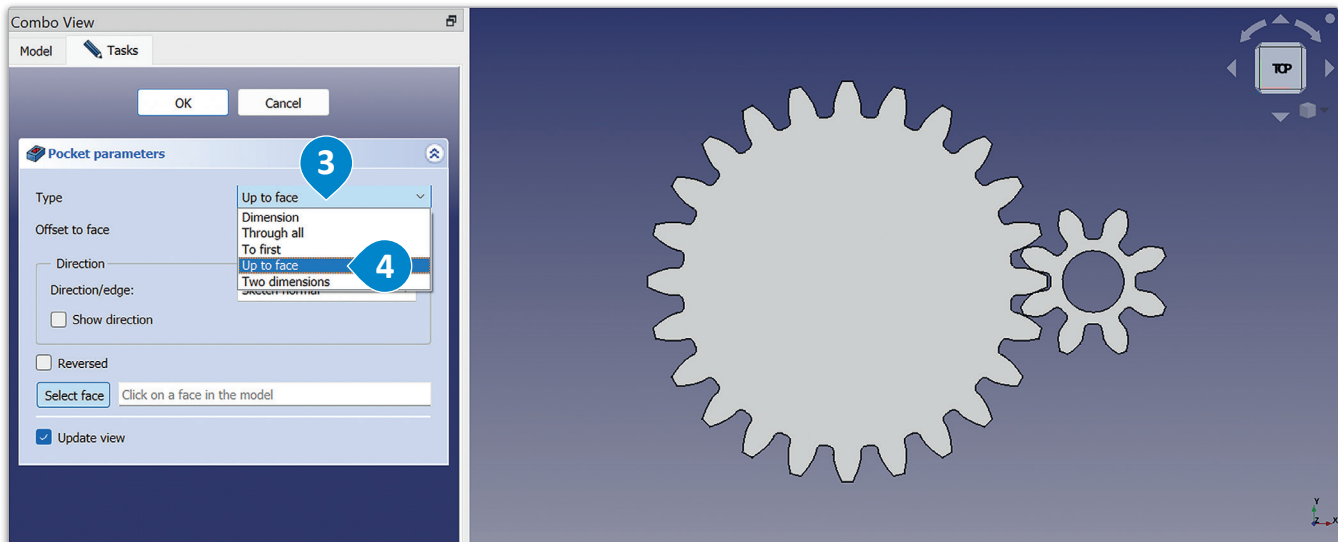
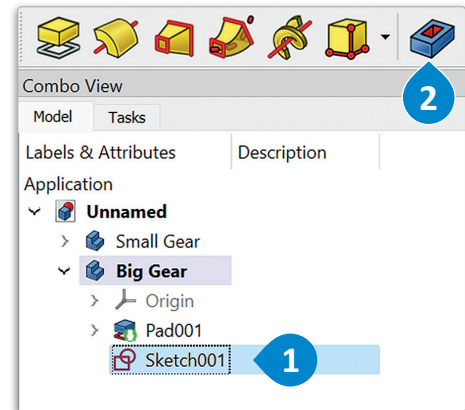


Figure 2.57: Creating a hole

Designing a Base to Connect the Gears

To complete the project, you need to create the base for the gears. The base will be a flat surface with two cylinders attached at a specific distance. This distance is crucial for the gears to work properly.

To create the base body:

- > From the **toolbar**, click the **Create body** tool. 1
- > From the **Data** tab, change the **Label** to **Base**. 2

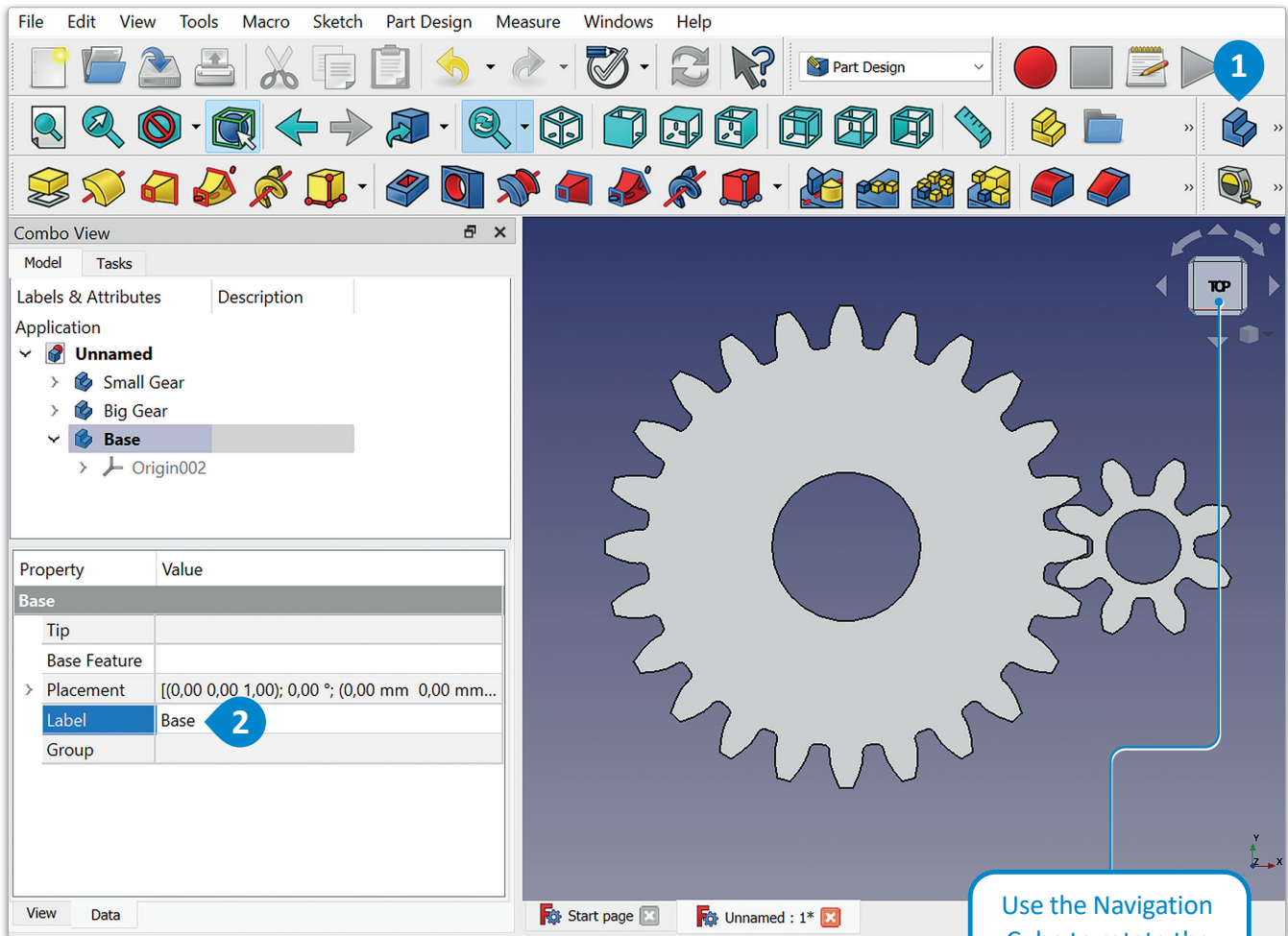
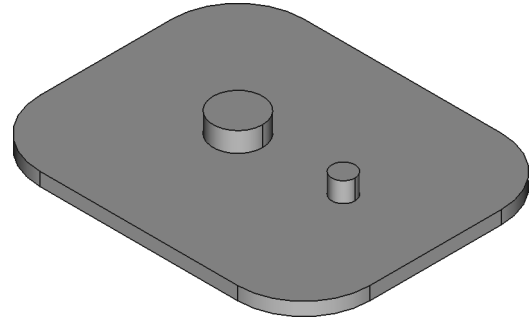


Figure 2.58: Creating base body

INFORMATION

The proper alignment of the gears is critical for effective teeth meshing, and this is accomplished by ensuring that the gears' axes are collinear, i.e., along a single line, and the gear centers are at a fixed distance from each other.

To start you will use the Create sketch tool to create a sketch in the XY plane.

To create a sketch:

- > From the **toolbar**, click the **Create sketch** tool. **1**
- > From the **Tasks** tab in the **Combo View**, click **XY_Plane**. **2**
- > From the **Tasks** tab in the **Combo View**, click **OK**. **3**

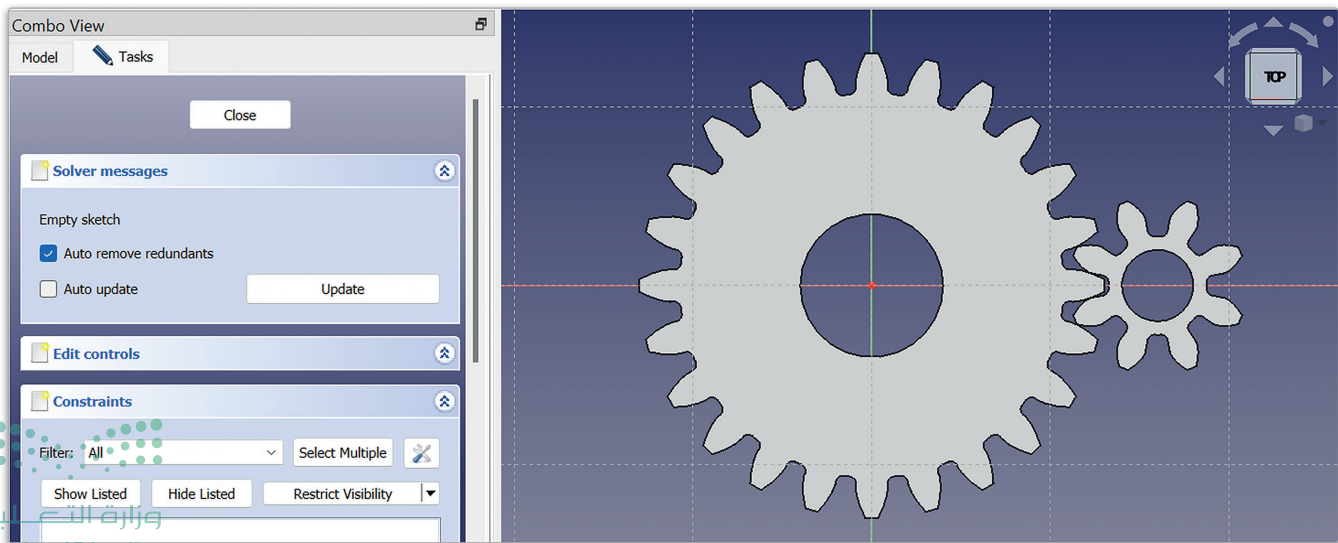
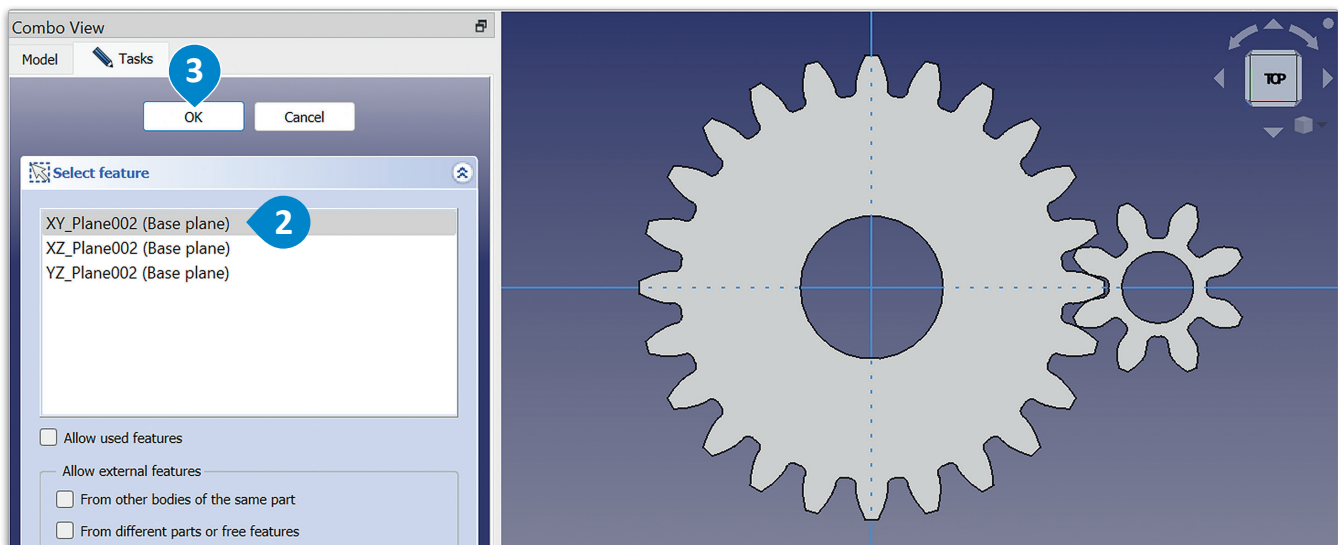
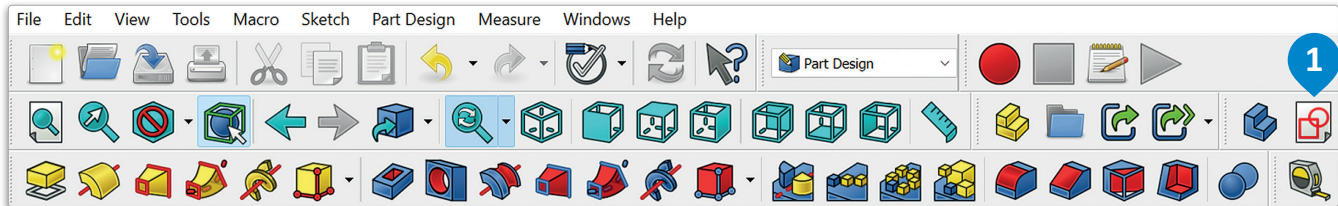


Figure 2.59: Creating a sketch

Now use the Create rectangles tool to create the perimeter of the base.

To create a rectangle:

- > From the **toolbar**, select the **Create rectangles** tool. **1**
- > Click on the sketch to set the first corner of the rectangle. **2**
- > Move the cursor to set the opposite corner of the rectangle, and click again to create the rectangle. **3**
- > From the **Tasks** tab, click **Close**. **4**

Don't forget to enable grid and grid snap to help you with the design.

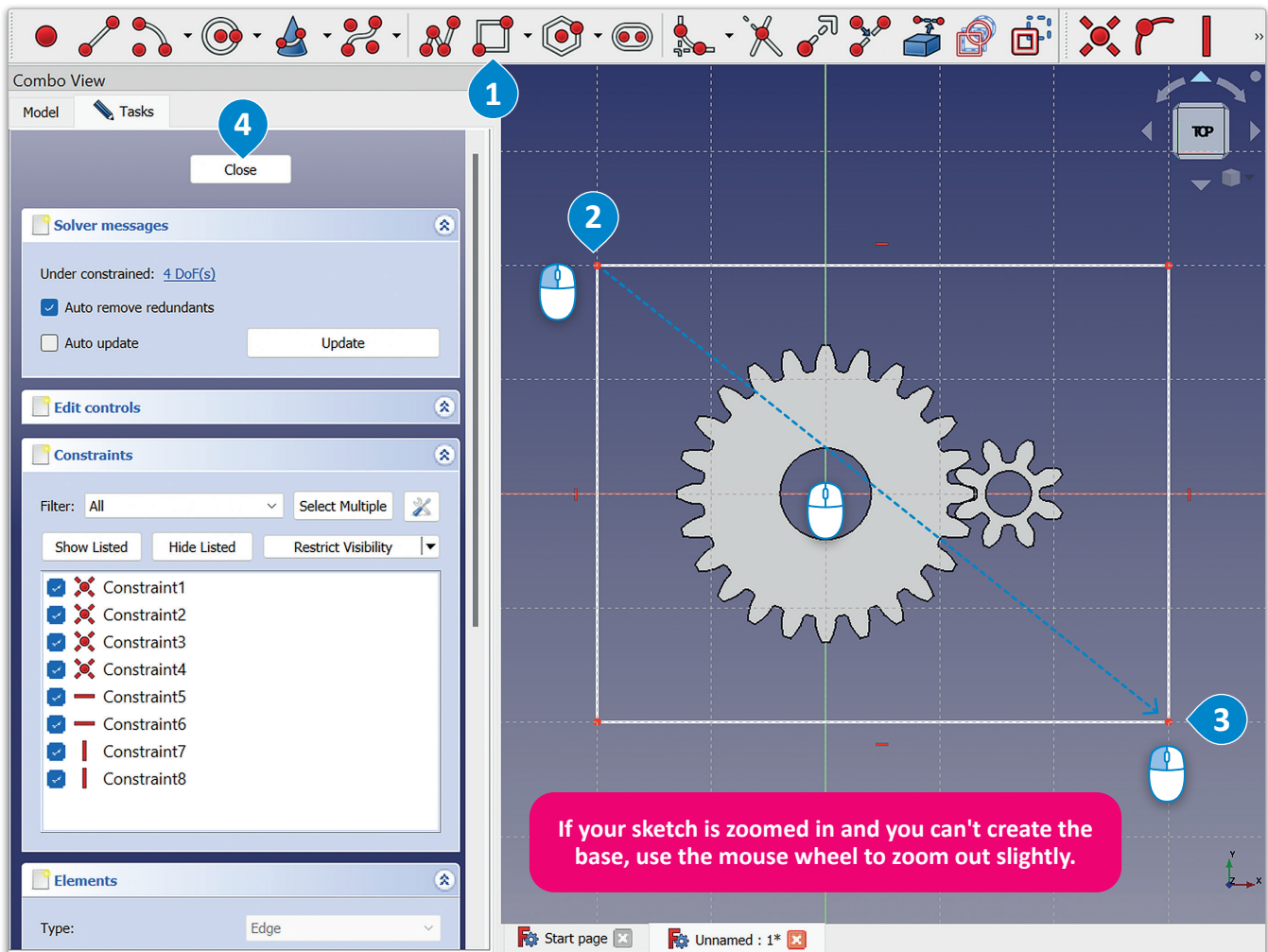


Figure 2.60: Creating a rectangle

INFORMATION

Not all sketches need to be fully constrained. In some cases, it may be sufficient to define only some of the constraints, or even no constraints at all, depending on the intended purpose of the sketch.

Then choose the Part Design workbench and use the Pad tool to change the rectangle into a 3D shape.

To create a 3D shape:

- > From the **workbench drop-down menu**, select the "**Part Design**" workbench. ①
- > From the **toolbar**, click the **pad tool**. ②
- > From the **Tasks** tab, change the length to **2 mm**, ③ and click **OK**. ④

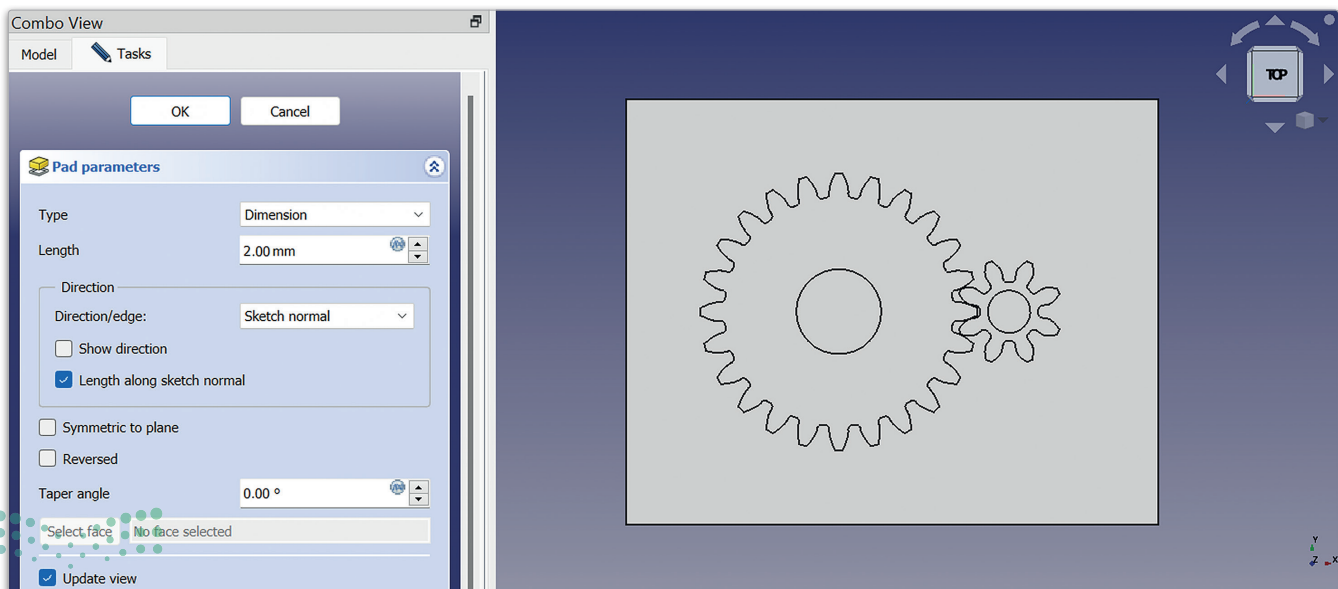
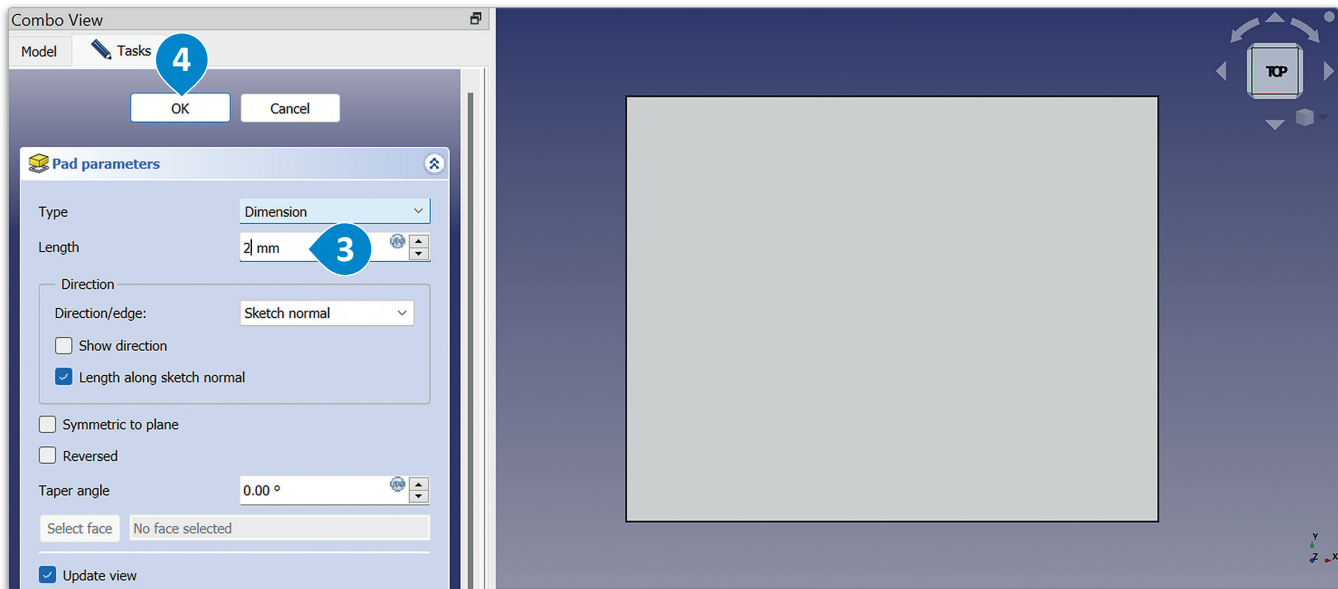
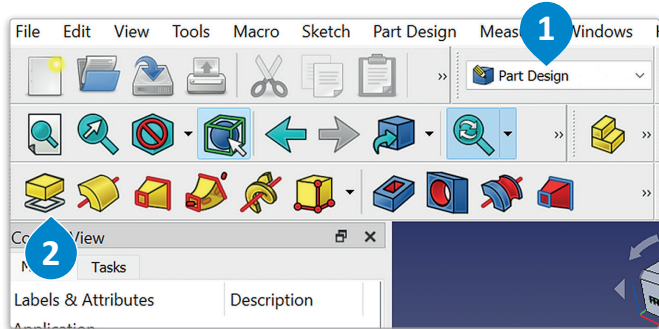


Figure 2.61: Creating a 3D shape

Return to the Model tab, and after selecting the top face of the base, use the Create sketch tool to create a new sketch that you will use it to create the first cylinder.

To create a sketch in the top surface of the Base:

- > From the **workbench drop-down** menu, select the "Part Design" workbench. **1**
- > Click the **Base** to select its top surface. **2**
- > From the **toolbar**, click the **Create sketch** tool. **3**

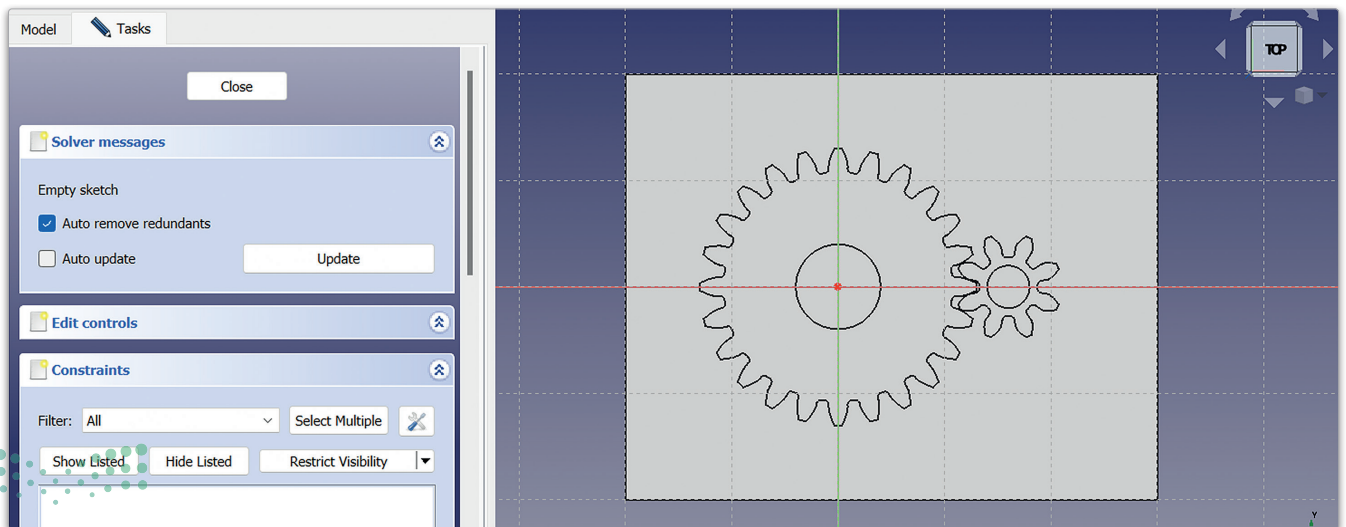
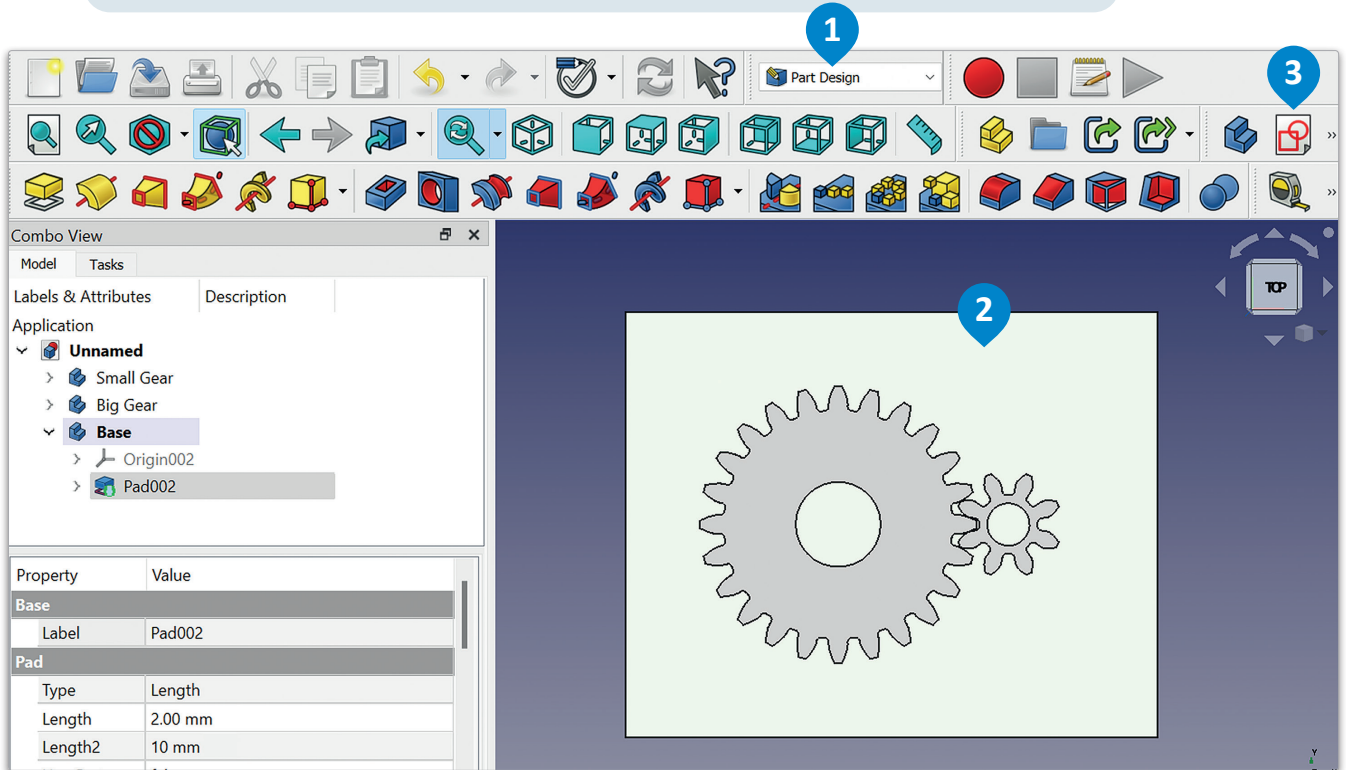


Figure 2.62: Creating a sketch in the top surface of the Base

Use the Create circle tool to create a circle for the hole and then use the Constrain radius tool to set the circle's radius to 3.75 mm.

To create the big circle:

- > From the **toolbar**, select the **Create circle** tool, **1** select the center of the axis **2** and click to create the circle. **3**
- > From the **toolbar**, select the **Constrain radius** tool **4** and click the circle. **5**
- > In the **Insert radius** window, type **3.75 mm** **6** and click **OK**. **7**

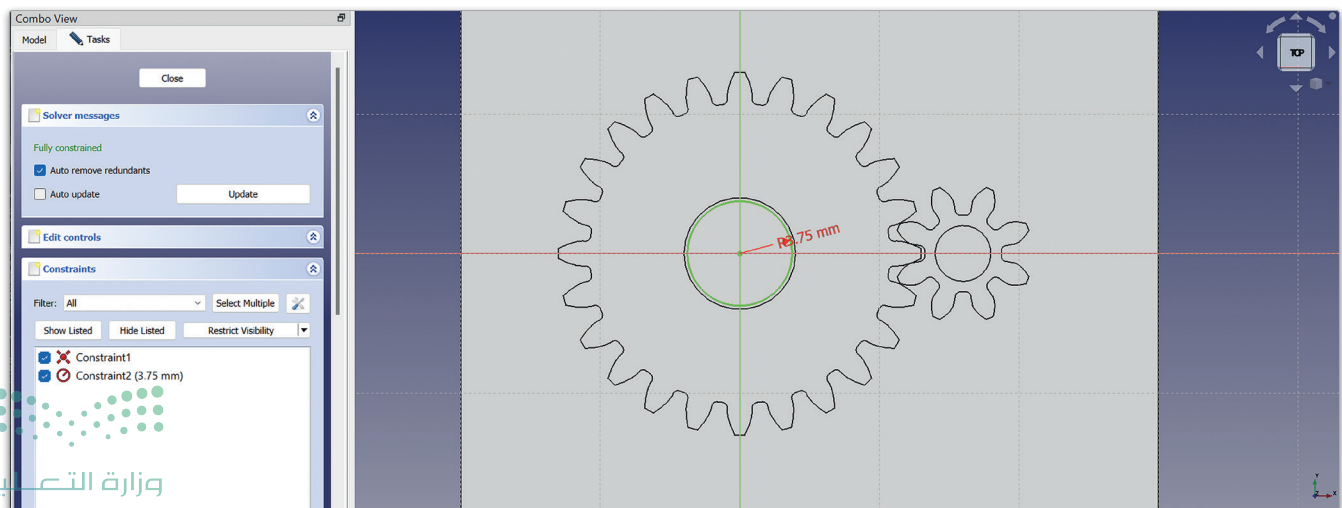
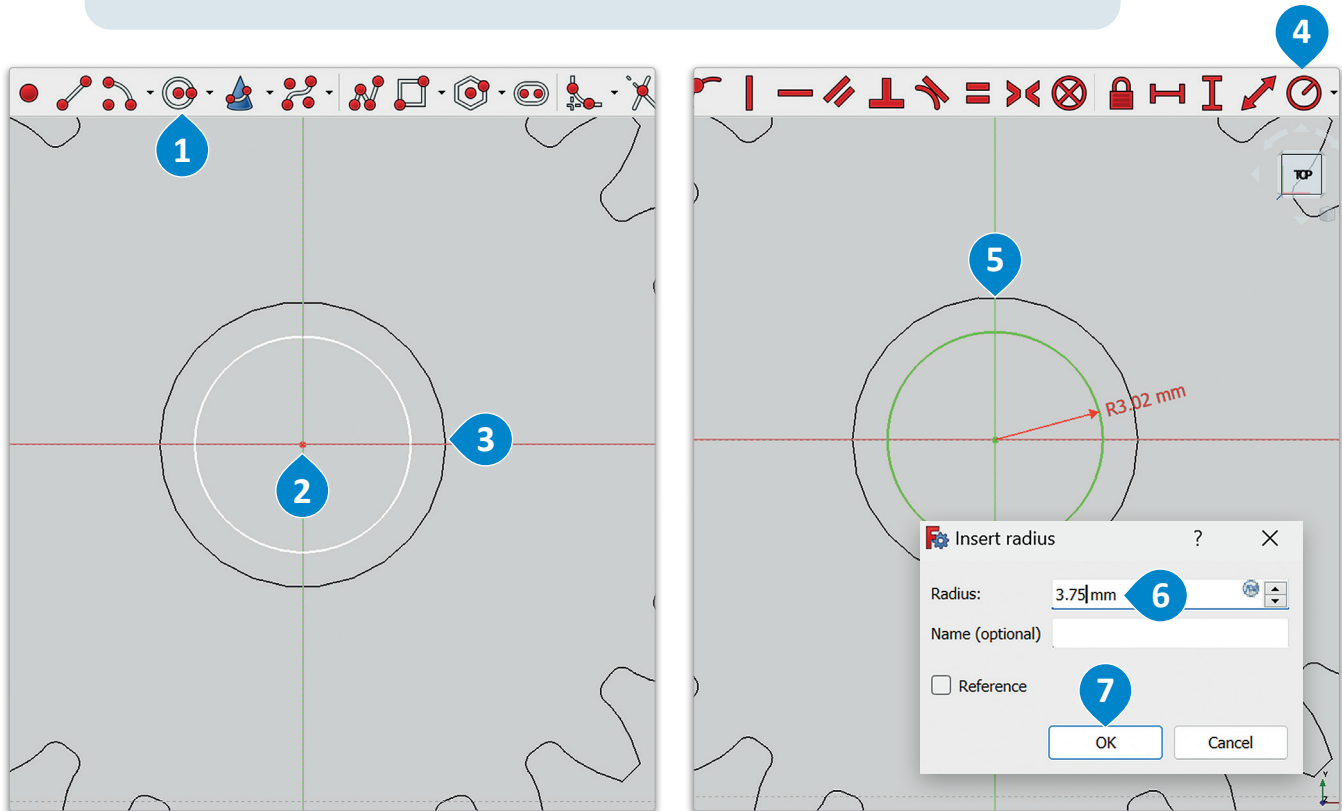


Figure 2.63: Creating the big circle

Finding the center for the big circle was simple because it was located at the center of the axis. Now, for the center of the small circle, you will use the Create point tool to create a point at exactly the right distance from the center of the big circle. The formula $\text{Distance} = (\text{Module} * (T1 + T2)) / 2$ you used earlier in the lesson tells us that the distance between the centers of the gears is 16 mm. Therefore, using the Constrain horizontal distance tool, you can set the distance between the centers of the two circles to 16 mm, thus defining the center of the small circle.

To create the center of the small circle:

- > From the **toolbar**, select the **Create point** tool, **1** and click in center of the hole in the small gear. **2**
- > From the **toolbar**, select the **Constrain horizontal distance** tool, **3** click the center of the big circle **4** and the point you have just created. **5**
- > In the **Insert length** window, type **16 mm** **6** and click **OK**. **7**

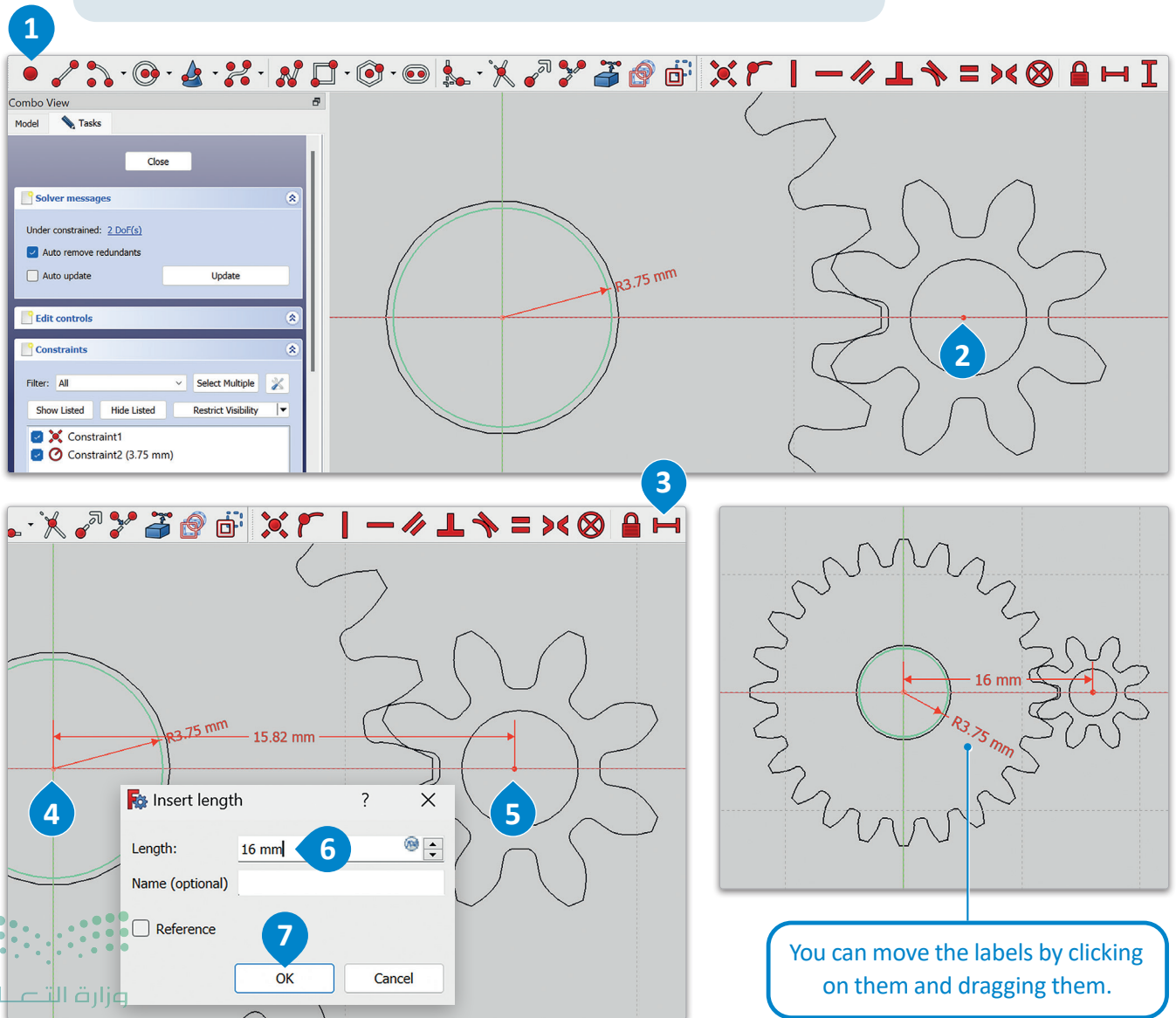


Figure 2.64: Creating the center of the small circle

Now that you have defined the center for the small circle, let's create it. You will use the Create circle tool to create a circle for the hole and then you will use the Constrain radius tool to set the circle's radius to 1.75 mm.

To create the small circle:

- > From the **toolbar**, select the **Create circle** tool, **1** select the center of the axis **2** and click to create the circle. **3**
- > From the **toolbar**, select the **Constrain radius** tool, **4** and click the circle. **5**
- > In the **Insert radius** window, type **1.75 mm** **6** and click **OK**. **7**
- > From the **Tasks** tab, click **Close**. **8**

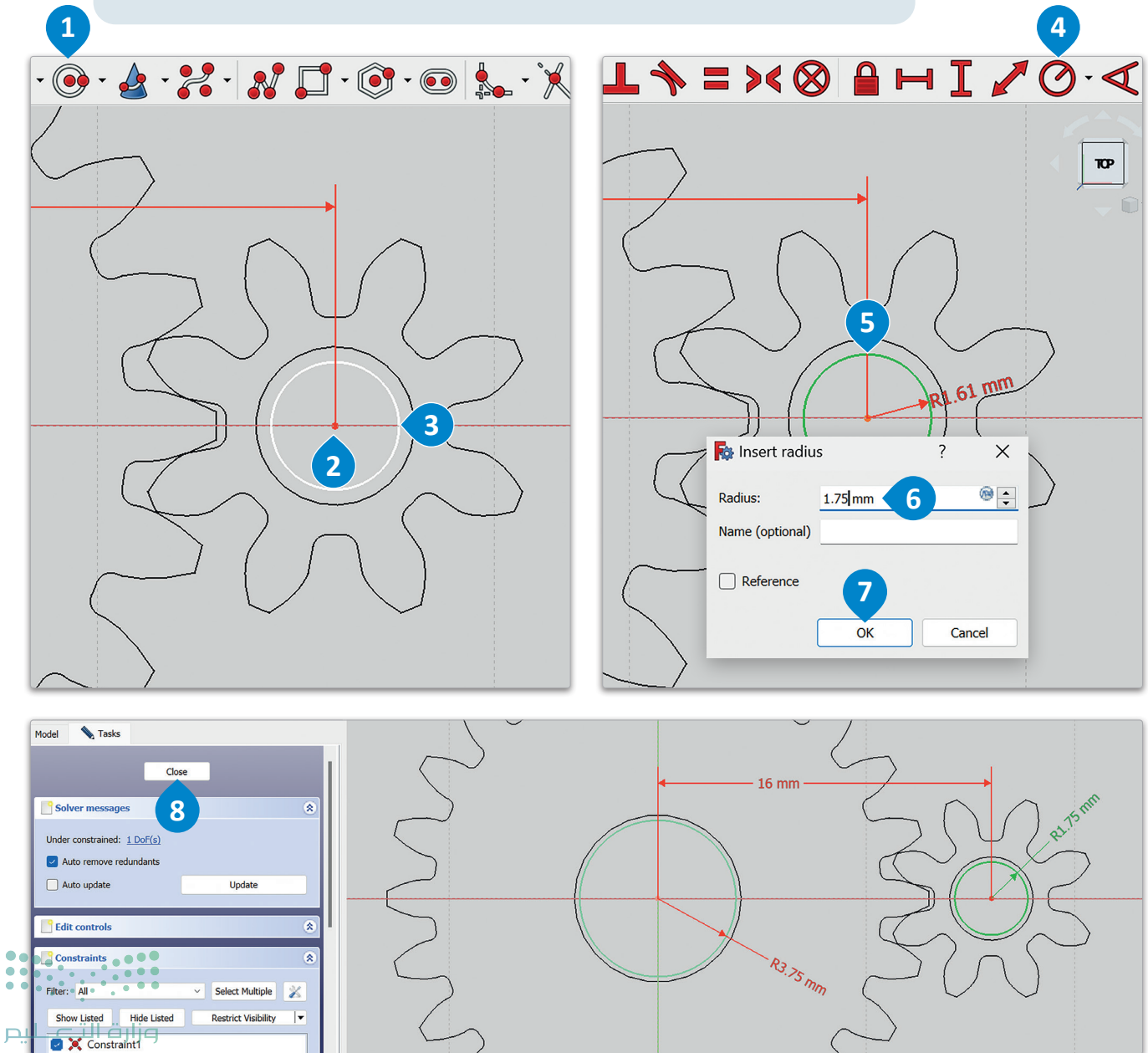


Figure 2.65: Creating the small circle

Now let's use the Pad tool to change the circles into cylinders.

To create the cylinders:

- > From the **toolbar**, click the **pad** tool. **1**
- > From the **Tasks** tab, change the length to **3 mm**, **2** and click **OK**. **3**

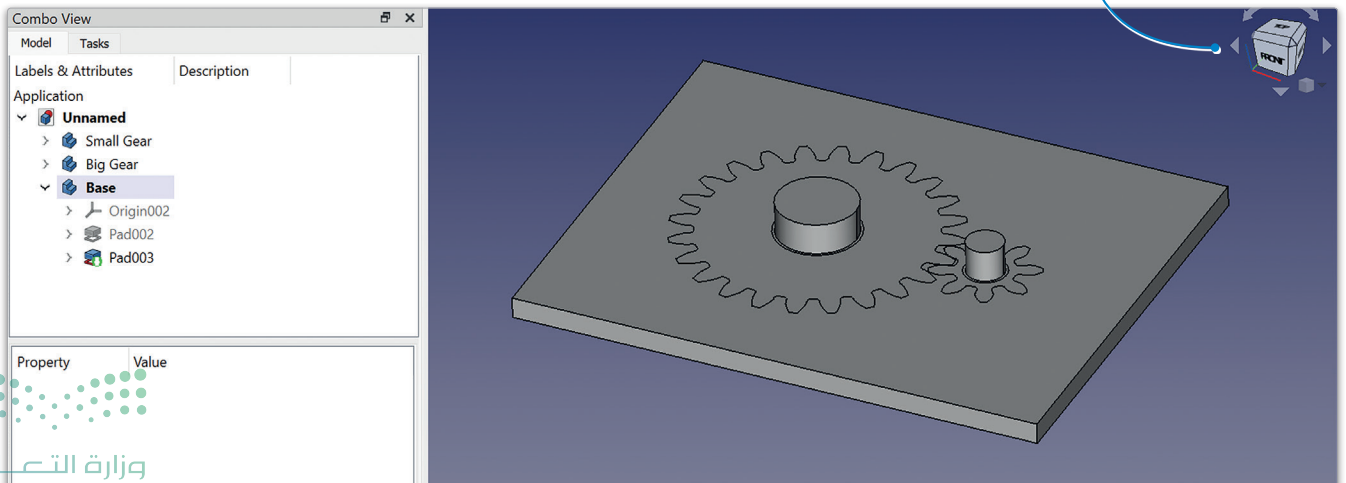
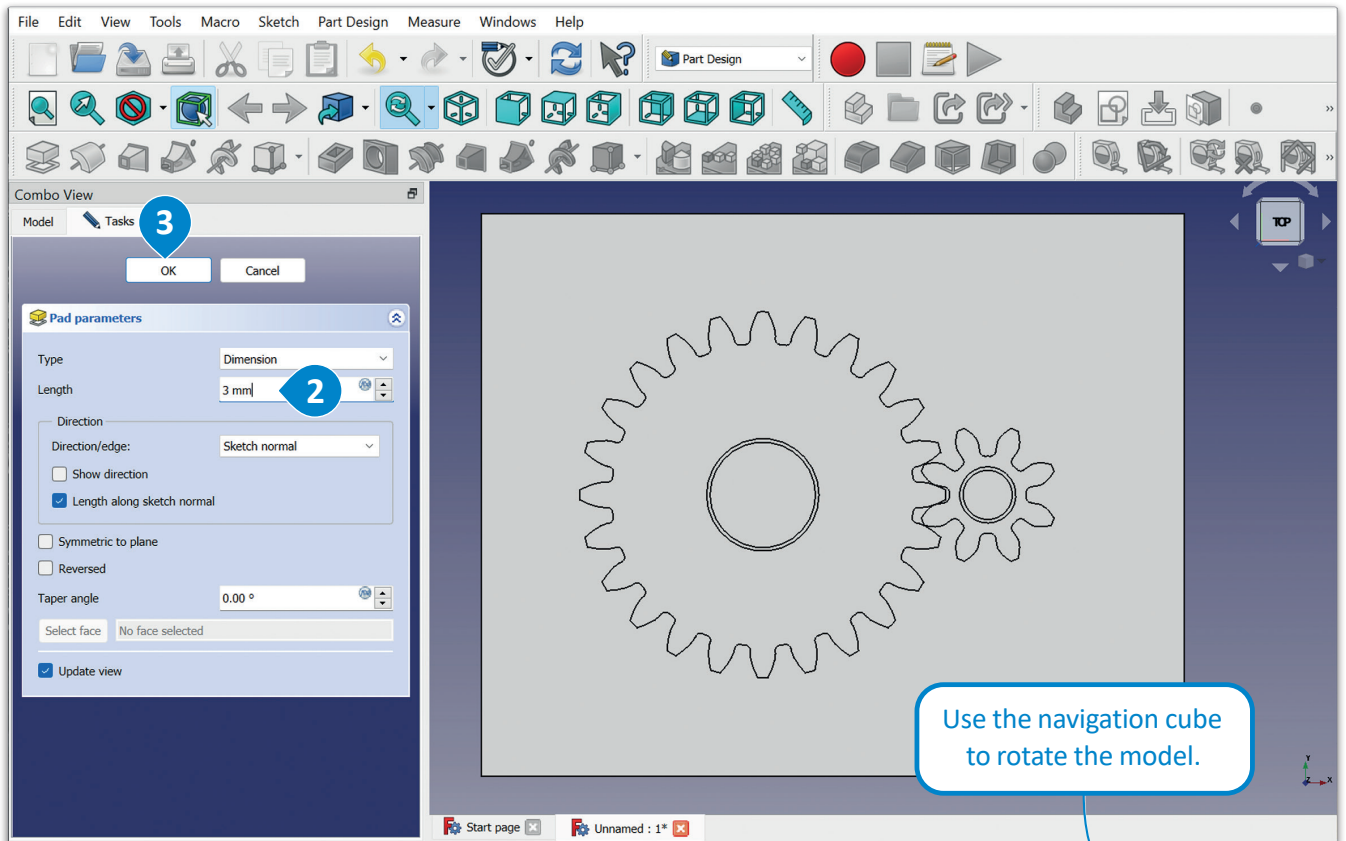
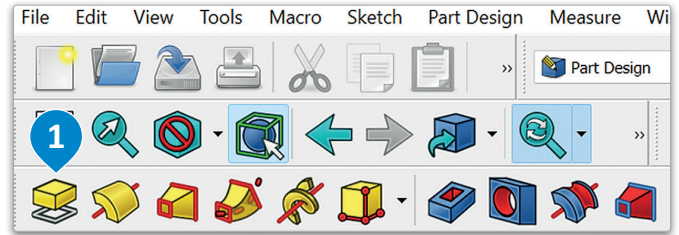


Figure 2.66: Creating the cylinders

Now that you have finished with the model you need to move the two gears 2 mm higher on the z axis.

To move the Gears:

- > From the **Model** tab, select **Small Gear**. **1**
- > From the **Data** tab, Click **Placement**. **2**
- > From the **Placement** drop-down menu click **Position**. **3**
- > In the **z** box in the **Position** drop-down menu type **2 mm**. **4**
- > From the **Model** tab, select **Big Gear**. **5**
- > In the **z** box in the **Position** drop-down menu type **2 mm**. **6**

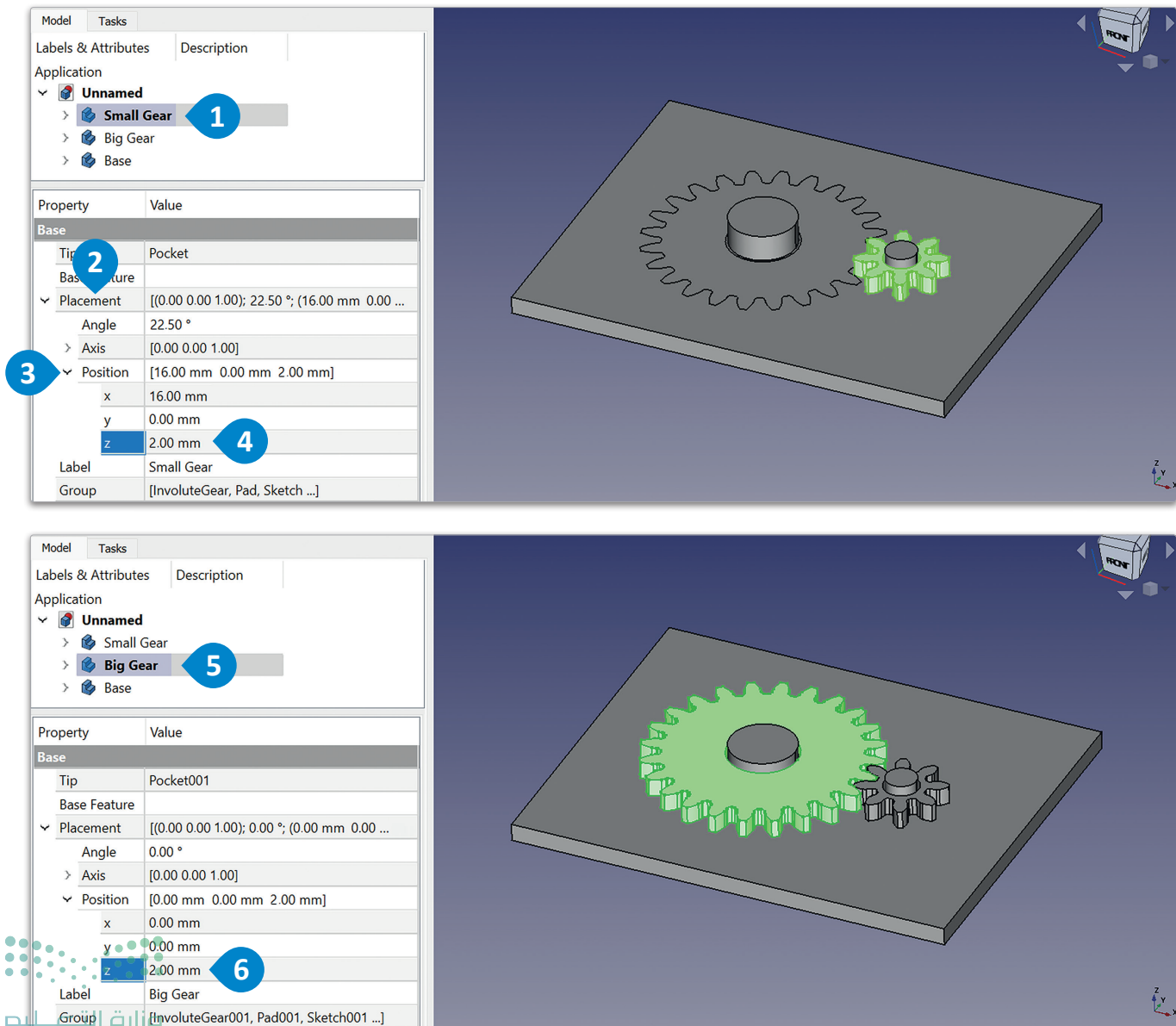
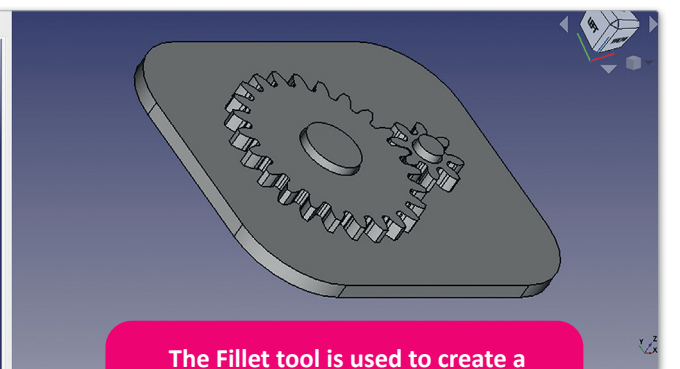
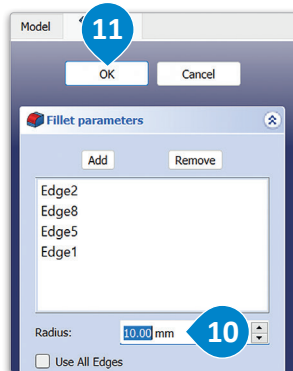
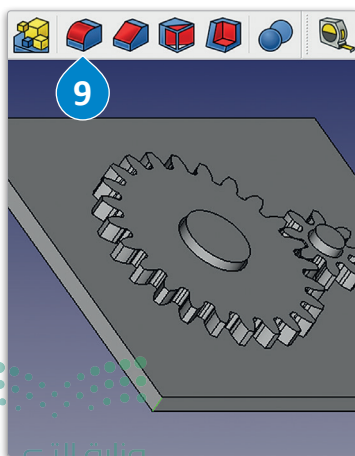
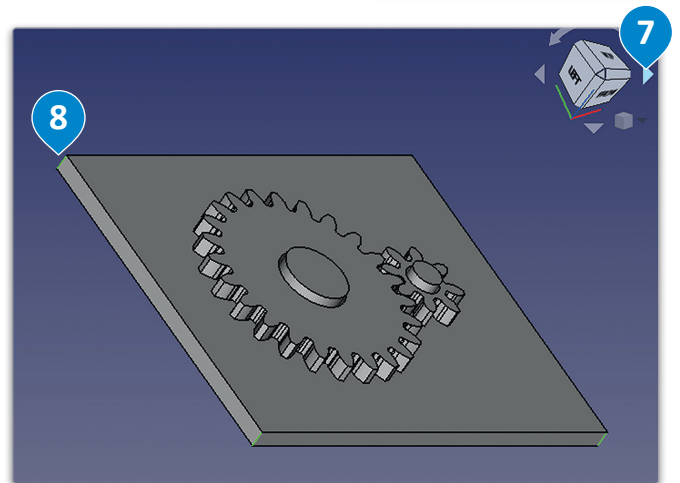
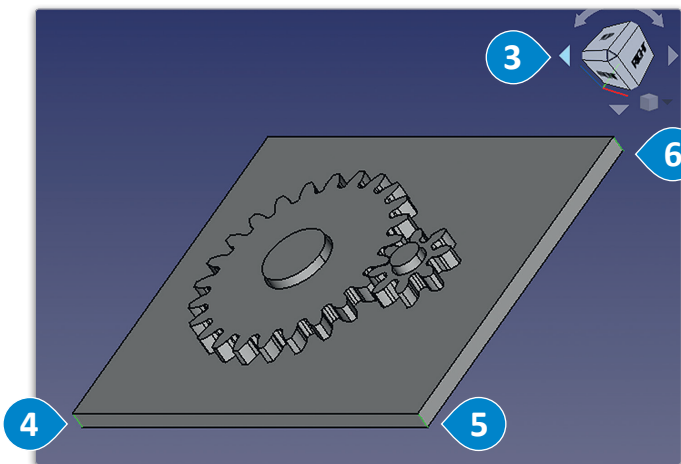
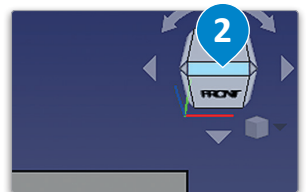
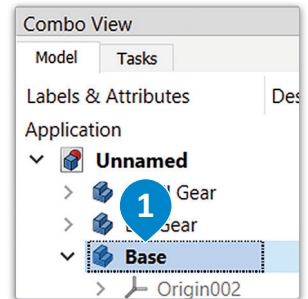


Figure 2.67: Moving the Gears

In the final step of this lesson, you will use the Fillet tool to give your base a more polished appearance. A fillet is a curved surface formed between two intersecting surfaces, and in this case, it will be used to create a smooth transition between the edges of the base. Adding fillets to your design can give it a more professional look and improve its functionality by reducing sharp corners.

To make the base curved:

- > From the **Model** tab, double click to select the **Base**. ¹
- > From the **Navigation cube**, click the corner to change the view. ²
- > From the **Navigation cube** click the left arrow. ³
- > Hold the **Ctrl** key and select the left lower corner, ⁴ the right lower corner, ⁵ and the right upper corner. ⁶
- > From the **Navigation cube** click the right arrow twice. ⁷
- > Hold the **Ctrl** key and select the upper left corner. ⁸
- > From the **toolbar**, select the **Fillet** tool. ⁹
- > From the **Tasks** tab, change the Radius to **10 mm**, ¹⁰ and click **OK**. ¹¹



The Fillet tool is used to create a smoother, more aesthetically pleasing model and to improve its functionality

Figure 2.68: Making the base curved

Finally, you will save your file.

To save your file:

- > From the **Menu bar**, click **File**, ¹ and select **Save**. ²
- > Click on the **Documents** tab. ³
- > Type a name, ⁴ and click **Save**. ⁵

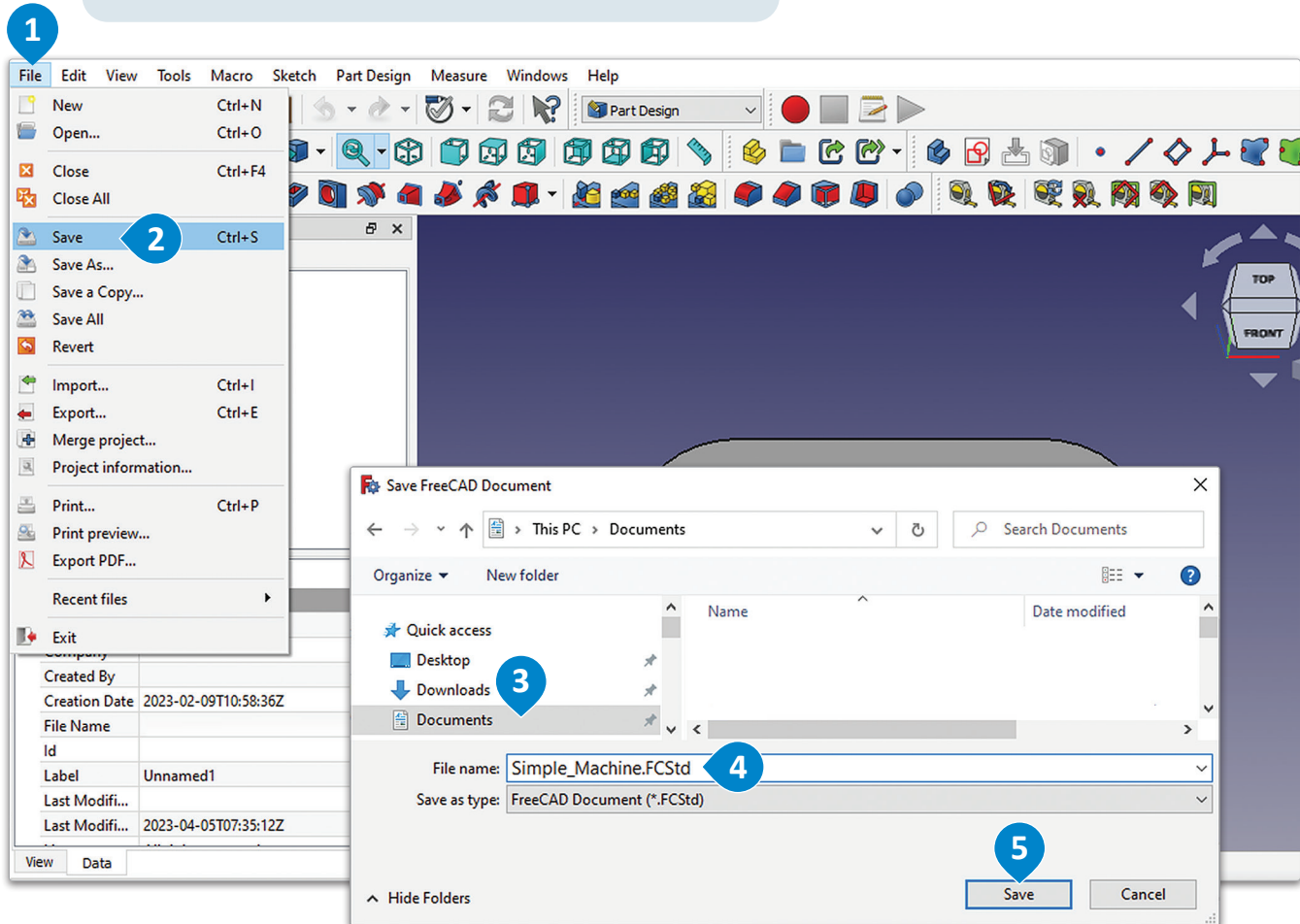


Figure 2.69: Saving your file

You have now designed your first mechanism. In the next unit, you will learn how to format the file to prepare it for printing.

A printed model with the assembled gear on the base



Exercises

1

Read the sentences and tick ✓ True or False.	True	False
1. Gears work together and can transmit power and motion.	☐	☐
2. A gear can be use to change speed and torque.	☐	☐
3. You can measure a gear by counting its teeth.	☐	☐
4. The drive gear is usually connected to a motion source (e.g. a motor).	☐	☐
5. The drive gear moves based on the movement of the driven gear and is connected to the movement destination (axis or cutting).	☐	☐
6. When the drive gear is bigger than the driven gear the speed increases.	☐	☐
7. The relationship between gears is expressed in terms of the ratio between the number of their teeth.	☐	☐
8. An involute gear is a type of gear that has an involute-shaped tooth profile.	☐	☐
9. Involute-based spur gears are suitable for applications requiring high torque.	☐	☐
10. The module is the pitch diameter divided by the number of teeth.	☐	☐

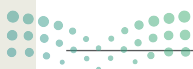
2 What are gears and how do they work?



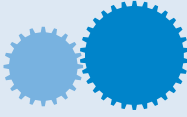
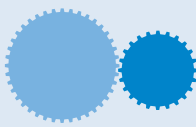
3 Explain how the gears work on a bicycle.

4 Search the Internet to find applications which use involute gears. Describe two applications and explain the characteristics of involute gears.

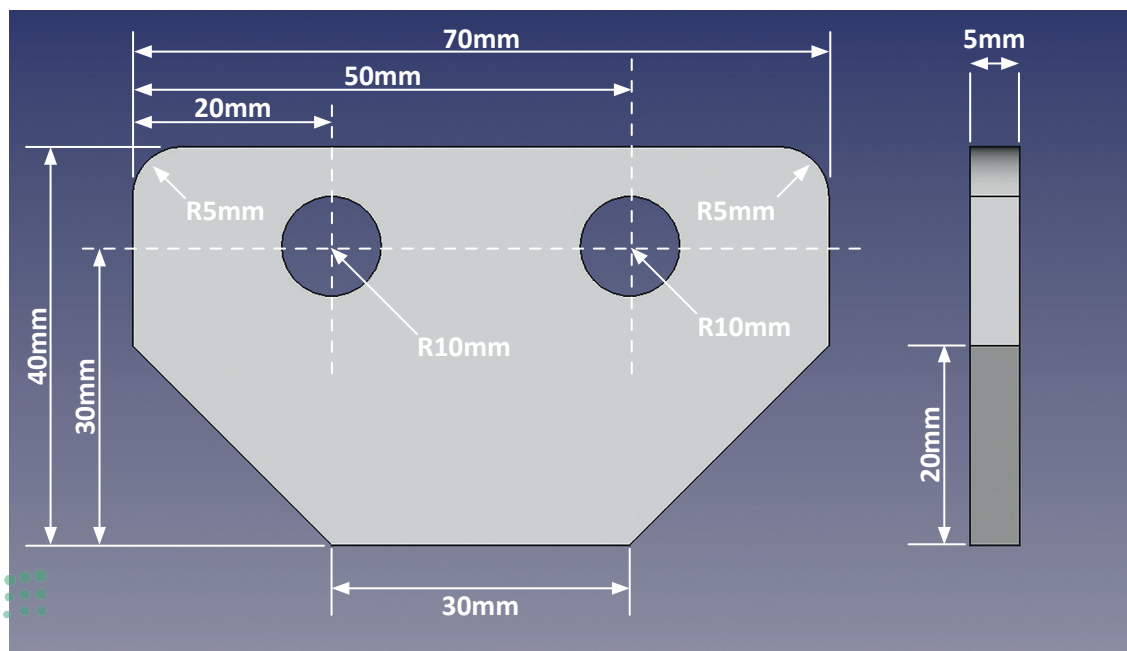
5 What is the importance of determining the center distance between two gears?



- 6 Use the formula for the gear ratio to calculate the ratio for each combination of gears. Mark with a tick ✓ which combinations of gears give increased speed and which give increased torque.

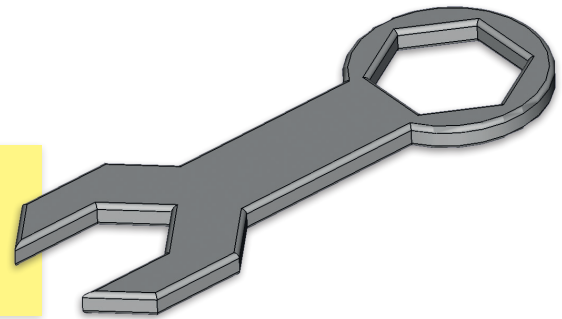
	Ratio	Increased Speed	Increased Torque
	Driving gear 8 Driven gear 40	☐	☐
	Driven gear 20 Driving gear 30	☐	☐
	Driven gear 4 Driving gear 24	☐	☐
	Driven gear 40 Driving gear 24	☐	☐

- 7 Use the tools from this unit to create the following model in FreeCAD. The following measurements will help you understand how each side is created.



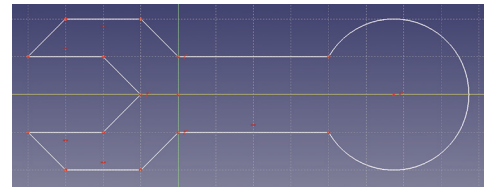
Project

In order to become proficient with producing 3D designs you need to create shapes that are useful. One of the most common and useful products you can create is a wrench.



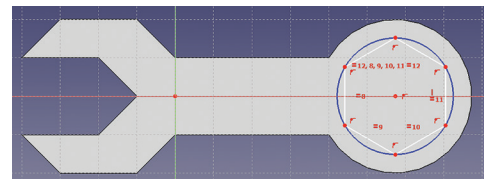
1

Use the Create line and Create polyline tools to make the perimeter of the Wrench.
Use the Create arc tool to make the arc of the Wrench.



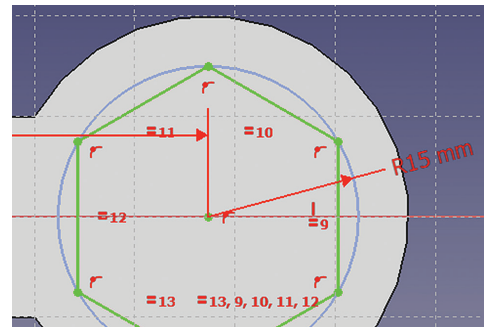
2

Use the Create hexagon tool to make the hexagon and then use the Pocket tool to create the hexagonal hole in the Wrench. The thickness of the Wrench should be 5 mm.



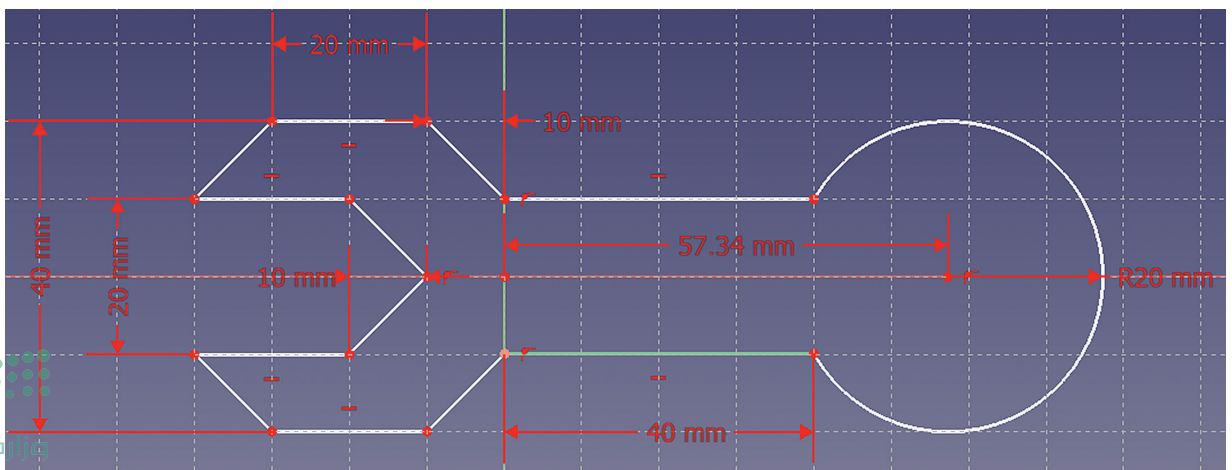
3

After creating the 3D model of the wrench, you can add details such as fillets to improve the appearance of the wrench.



4

Use the following sketches to design the Wrench.



Wrap up

Now you have learned to:

- > Design and prototype.
- > Use the FreeCAD software application.
- > Use workbenches in CAD software.
- > Create basic 2D and 3D shapes.
- > Add constraints to objects.
- > Use planes to define the position and orientation of objects.
- > Use 3D views.
- > Use multiple bodies to create more complex 3D designs.
- > Use gears to create a simple machine.

KEY TERMS

Constraints	Oblique drawing	Planes
Exploded views	Orthographic Projection	Prototype
Extrude	Padding	Workbenches
Isometric drawing	Perspective drawing	



3. 3D Product Development

In this unit, you will learn about 3D printing technology and its applications. You will learn about the types of printers and materials used in 3D printing. You will also gain an understanding of the various stages of testing and refining 3D-printed products and the tools used for this process. Moreover, you will design a complex 3D object using FreeCAD and then use Cura slicing software to print it. In addition, you will learn about the constraints involved in testing and refining 3D printed products and the importance of quality control in the 3D printing process.

Learning Objectives

In this unit, you will learn to:

- > Describe the uses of 3D printing.
- > Classify the types of 3D printers.
- > Outline the types of 3D printing materials.
- > Analyze the applications of 3D printing.
- > Print a complex 3D printed object with Cura.
- > List the various stages of testing and refining 3D printed products.
- > Examine the tools used for testing and refining 3D printed products.
- > Identify the constraints when testing and refining 3D printed products.

Tools

- > FreeCAD
- > Cura



Lesson 1

Introduction to 3D Printing

Link to digital lesson



www.ien.edu.sa

Basics of 3D Printing

Three-dimensional (3D) printers produce a physical object from a three-dimensional digital model file by applying numerous thin layers of selected material in succession. The first step in 3D printing is to create a 3D model of the object you want. You can create a model with 3D modeling software or scan the object with a 3D scanner. The output of the 3D printer varies depending on the type of printer and the materials used. The most common industrial prototyping and production materials are plastics, metals, ceramics, and sand. There is also advanced research underway for biomaterials to be used in the food industry to produce 3D-printed food. Several affordable 3D printers are available for beginners.

Engineers and designers use 3D printers to test prototypes. Manufacturing businesses use them to fabricate complex parts for assemblies. In addition, businesses and individuals can use them for DIY (Do It Yourself) fabrication. DIY fabrication refers to creating or building something using tools, materials, and techniques commonly available to individuals without professional training or specialized equipment. 3D printers are tools; they allow people to build things they could not have previously built. 3D printing is a hands-off manufacturing procedure. Traditionally, engineers had to run drill presses, lathes, and milling machines. Aligning, measuring, and machining the workpiece introduces human error and challenges for achieving high precision. 3D printing allows for the production of complex and intricate objects with minimized probability of human error. Examples of human error are leveling the bed, proper settings of the slicer software, and proper manufacturing settings.

History of 3D Printing

In the 1980s, 3D printing was named Rapid Prototyping (RP). RP is a process for rapidly creating a representation of a part or a system before final release or commercialization. The techniques were originally intended as a fast and cost-effective way to create industrial prototypes. Dr. Hideo Kodama submitted the first RP patent in Japan in May 1980. Stereolithography (SLA) was the first commercial 3D printing process and was developed in the 1980s.

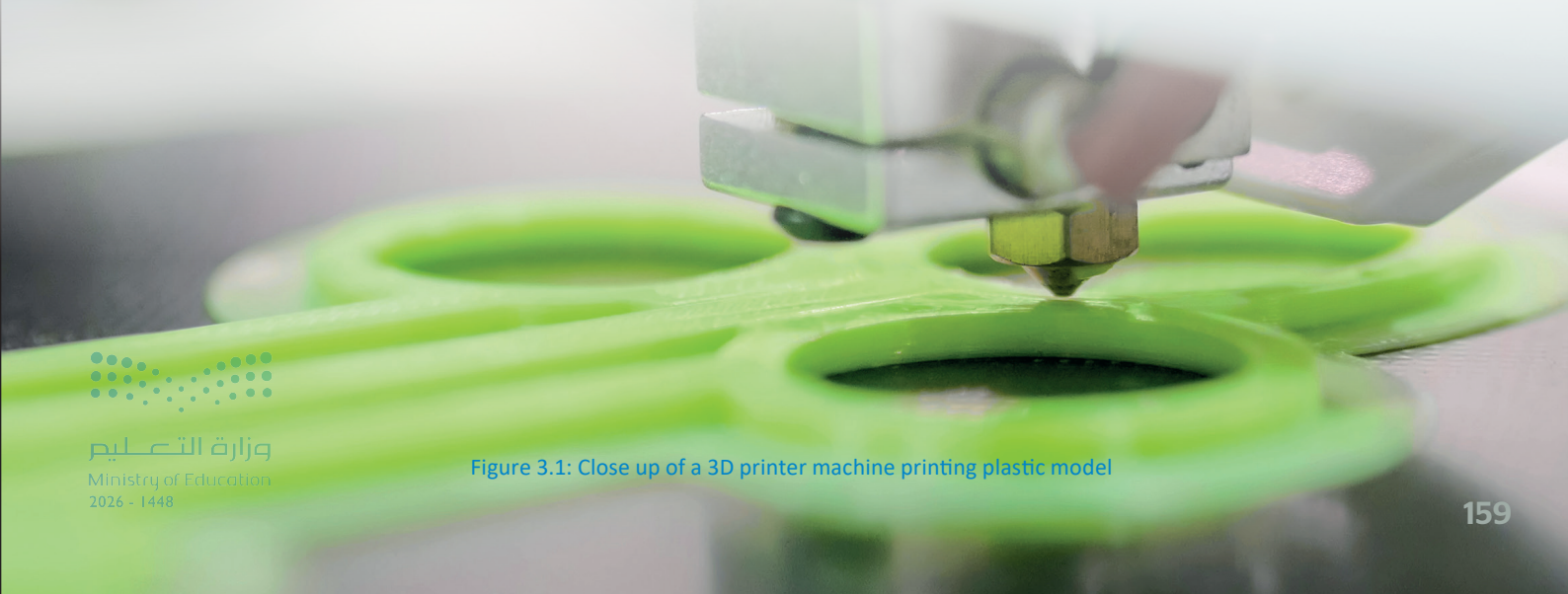


Figure 3.1: Close up of a 3D printer machine printing plastic model

Types of 3D printers

Three-dimensional printing is a type of additive manufacturing where material is added layer by layer to create a three-dimensional object. Additive manufacturing processes are classified into several kinds including powder bed fusion, material extrusion, vat polymerization, sheet lamination, binder jetting, and directed energy deposition. These processes involve fusing or depositing material layer by layer using different techniques such as a high-energy laser or electron beam, heated nozzle, liquid resin, cutting and bonding sheets of material, depositing a binder material, or melting and depositing material with a high-energy source.

Stereolithography

Stereolithography (SLA) is a laser-based method that uses photopolymer resins to make precise parts. The photopolymer resin is in a vat with a moveable platform held by support structures. A heated laser is emitted in the X-Y axes across the resin's surface based on a 3D model, hardening the resin exactly where the laser hits. Once a layer is complete, the vat's platform moves in the Z axis, and the laser traces the next layer. The process continues until the object is complete, and the platform may be removed. Objects created with using this type of printers must be cleaned and cured after printing. Curing uses intense light in an oven-like mechanism to harden the resin. Stereolithography is one of the most accurate and smooth 3D printing technologies. Its main limitations are the post-processing procedures and the object's brittleness over time. Figure 3.2 shows an object printed with the SLA method.



Figure 3.2: Object photopolymer printed on a 3D printer

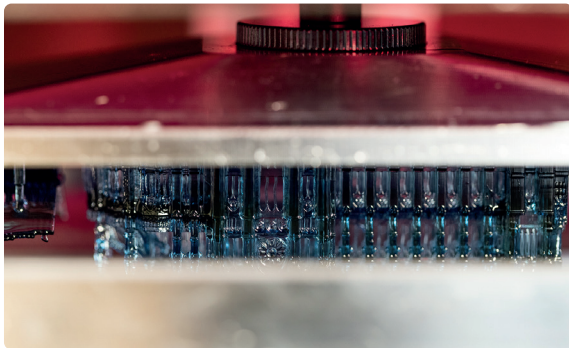


Figure 3.3: Digital Light Processing 3D printing

Digital Light Processing

Digital Light Processing (DLP) is a 3D printing technology that, like SLA, uses photopolymers. The difference is in the light source. DLP employs a common light source with an Liquid Crystal Display (LCD) panel or a Deformable Mirror Device (DMD) applied in a single pass to the vat of photopolymer resin, making it faster than SLA. DLP generates high-resolution objects but has the same support structure and post-curing requirements as SLA. DLP has the advantage of requiring only a shallow vat of resin, which reduces waste and operating expenses. Figure 3.3 shows the process of DLP printing.

Laser Sintering and Laser Melting

Laser is used in the sintering and melting process, also known as selective laser melting, to fuse powdered material into a solid object, layer by layer. The powder bed acts as a support structure, making complicated designs possible. Porosity and long cooling times present challenges for this technology, but progress has been made toward printing more dense objects. Laser sintering can process both plastic and metal, with metal requiring a more powerful laser and higher temperatures. This method produces stronger parts than SLA or DLP but with less precision and polish. Figure 3.4 shows an engine part printed with laser sintering.



Figure 3.4: Object printed in laser sintering machine

Fused Deposition Modeling

Fused Deposition Modeling (FDM), which is cheap, affordable, and available widely, melts plastic filament and deposits a layer onto a build platform using 3D data. Each layer hardens and binds as it is deposited. Overhanging geometries require support structures. Basic FDM printers lack support structures but this can be mitigated because these systems feature two extrusion heads. A second extrusion head emitting a water-soluble substance can be used to create support structures which can be washed away after printing. Breakaway support materials that can be removed by hand are also used. The FDM method is accurate and reliable, but it can require extensive post-processing. It can also be slow when reproducing complex geometries and layer-to-layer adhesion can cause leaky parts. Early FDM devices produced less accurate models, but model accuracy is improved with each new generation of printers. Figure 3.5 shows gears produced by FDM.



Figure 3.5: Gears produced by small black FDM printer

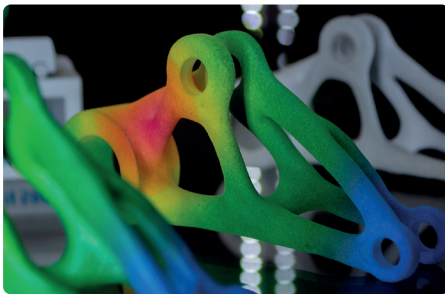


Figure 3.6: Model printed with binder Jetting process

3D Inkjet Printing

Binder Jetting

Binder Jetting selectively sprays a binder into a powder base material to create a fusion layer by layer to create the final object. Once a layer is completed, the powder base descends incrementally, and a roller or blade smooths the powder across the base to prepare the next layer. This method can also quickly add a full-color palette to the binder to create objects with more colors. The machine's parts are not as durable as those in other printer types, and the final objects require post-processing and cleaning. Figure 3.6 shows a model printed with binder jetting.

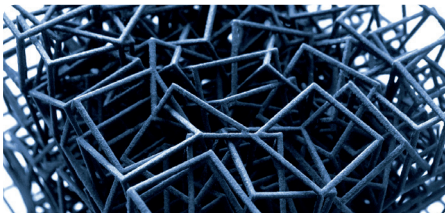


Figure 3.7: Model printed with Material Jetting process

Material Jetting

Material Jetting is a 3D printing method where liquid or molten build materials are jetted through several jet heads. As each layer is deposited, ultraviolet (UV) light cures liquid photopolymers. This device allows the simultaneous layering of several materials so that a single part can be made from materials with different properties. Material Jetting produces precise, smooth, 3D-printed items. Figure 3.7 shows a complex cubical model printed with material jetting.

Selective Deposition Lamination

Selective Deposition Lamination (SDL) 3D printing uses copier paper and adhesive material for the object layers. A higher quantity of adhesive is emitted in the area that will become the main structure of the object, and a lesser quantity is put in the surrounding area that will act as the support. A paper layer is fed into the printer and applied to the adhesive of the previous layer. Then the build plate is heated and pressed. This pressure bonds the two papers with the adhesive material. The build plate returns to the original position, where an adjustable Tungsten carbide blade cuts each paper layer to produce the part edges. Figure 3.8 shows copier paper that can be used for SDL printers.



Figure 3.8: SDL 3D printer using copier paper



Figure 3.9: EBM alloy component

Electron Beam Melting

In Electron Beam Melting (EBM), the heat source is an electron beam, not a laser; this method must therefore be performed under a vacuum. EBM can create fully dense parts in various metal alloys, allowing for precision and customization in the final product. EBM is used heavily in the automobile and aviation industries to manufacture complex parts. Figure 3.9 shows a complex spherical component printed with EBM.

Table 3.1 illustrates the main advantages and disadvantages of each 3D printing technology.

Table 3.1: Advantages and disadvantages of 3D printing technologies

Advantages	Disadvantages
Stereolithography	
High accuracy and resolution, smooth surface finish, can produce complex geometries	Limited material options, high operating costs, post-processing is required
Digital Light Processing	
High speed, high resolution and accuracy, good surface finish	Limited material options, high cost of equipment, post-processing is required
Laser Sintering and Melting	
Can produce strong and durable parts, can use a variety of materials including metals, good for producing complex geometries	High cost of equipment, long cooling times, poor surface finish
Fused Deposition Modeling	
Low cost of equipment, large variety of materials available, fast print speeds	Poor surface finish, limited accuracy and resolution, slow when reproducing complex geometries
Binder Jetting	
Can produce large objects quickly, low cost of equipment, good surface finish	Limited material options, it's parts are relatively weak, poor accuracy and resolution
Material Jetting	
High accuracy and resolution, good surface finish, can produce multi-material objects	Limited material options, high cost of equipment, not suitable for producing large objects
Selective Deposition Lamination	
Can produce large objects, low cost of equipment, good for producing color models	Limited material options, copier paper and adhesive material are relatively weak, poor surface finish
Electron Beam Melting	
Can produce complex and high-performance metal parts, high accuracy and resolution, good surface finish	High cost of equipment, limited material options, post-processing is required

3D Printing Materials

Since 3D printing's early days, materials used to create 3D objects have improved. There are several materials in different states with different chemical properties. Specific materials are now produced for platforms performing dedicated applications, with qualities adapted to each application.

Plastics

Nylon is used in powder form for sintering and in filament form for FDM. It is a robust, flexible, and durable 3D-printing plastic. It is white but can be colored pre- or post-printing. Nylon can be used with powdered aluminum to make 3D printing materials. Acrylonitrile Butadiene Styrene (ABS) is another common 3D printing resin used in filament form on basic FDM printers because it is a strong and colorful plastic, as shown in figure 3.10. It is popular due to its accessibility on the market. Polylactic Acid (PLA) is used as an adhesive for printing in DLP/SLA resin and FDM filament techniques. It comes in many colors, including transparent, which is ideal for 3D printing, although it is less durable and flexible than ABS.



Figure 3.10: Plastic materials for 3D printing

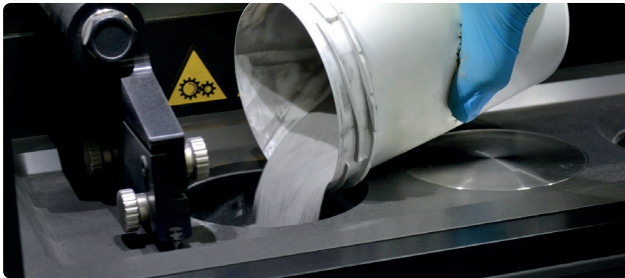


Figure 3.11: Stainless steel powder for 3D printing

Metals

Stainless steel powder is one of the strongest and most commonly used metals for various 3D printing applications as shown in figure 3.11. Steel can be coated to look like gold or bronze, although gold and silver may be 3D printed directly, with obvious jewellery applications. Titanium in powder form is one of the strongest metals for industrial sintering and EBM 3D printing.

Ceramics

Ceramics can be 3D printed for cosmetic applications or applications that need a specialized material. After printing, the ceramic sections must be fired and glazed, just like traditional applications of ceramic materials as shown in figure 3.12.



Figure 3.12: 3D Printing with ceramic material

Paper

Standard copier paper is mainly used in applications of SDL 3D printing. The main advantage of paper is that it is easily obtainable, cheap, and can be bought in large quantities. The 3D objects created with paper and the SDL method are environmentally safe, can be recycled easily, and require little post-processing and cleaning. Figure 3.13 shows full color printed model of a fruit.

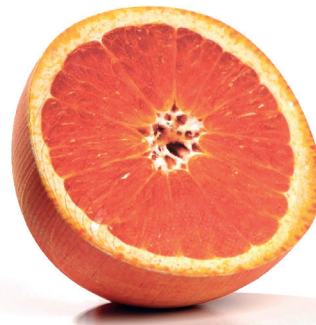


Figure 3.13: Full color printed model

Biomaterials and Food

3D printing biomaterials for biomedical applications are being researched extensively. Leading institutions are developing living tissue to print human organs for transplant and external tissues when some members need to be replaced in body parts. Other research focuses on developing food materials for 3D printing, like meat, sugar, and pasta. Future research aims to use 3D printing to create affordable and nutritious 3D-printed meals. Figure 3.14 shows the use of a 3D bioprinter.

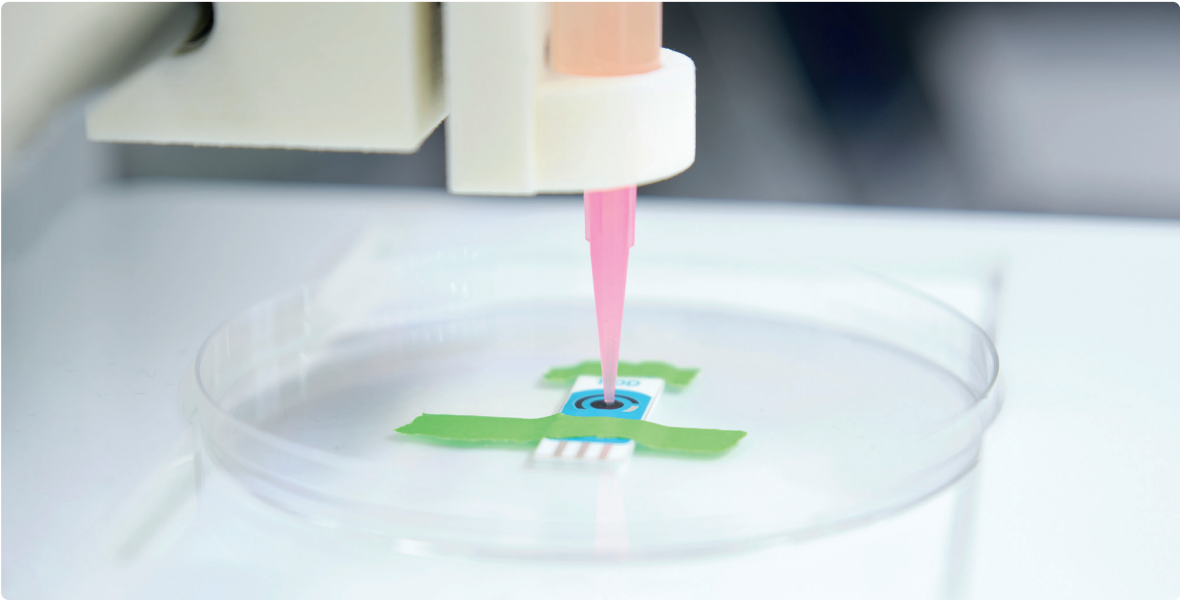


Figure 3.14: 3D bioprinter ready to 3D print cells onto an electrode

Benefits of 3D Printing

There are numerous advantages to 3D printing in various application areas, whether personal, commercial, or industrial. Table 3.2 illustrates the main benefits of 3D printing.

Table 3.2: Benefits of 3D printing	
Benefit	Description
Speed	3D printing provides the ability to produce a physical object in a matter of hours or even minutes, compared to traditional manufacturing methods that can take days or weeks.
Customization ability	3D printing allows mass customization of products to specific needs. 3D printing allows several products to be made in the same build chamber at no additional cost.
Manufacturing complex components	3D printing has led to the creation of complicated objects that could not otherwise be made. Designers and artists have used this advantage to great effect. It has also impacted industrial applications, which are developing applications to produce complicated components that are lighter and stronger than their predecessors.

Benefit	Description
Tool-less	Tool production is a costly, time-consuming, and labour-intensive stage of industrial product development. Industrial 3D printing can eliminate tool production costs, lead times, and labour for low to medium-volume applications. Many businesses are taking advantage of this valuable opportunity. Due to the complexity advantages mentioned above, products and components can be designed to avoid elaborate geometry and complex features, further reducing assembly labour and costs.
Sustainability	3D printing is also an energy-efficient technique that can eliminate waste during manufacturing and extend the product's operating life with a lighter, stronger design with a lower carbon footprint than traditionally created products.
Ease of use	3D printing provides a simple workflow, which allows individuals with limited technical knowledge to design and print objects without requiring specialized skills or training.

Applications of 3D Printing

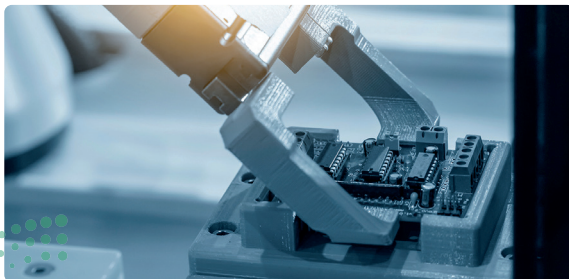
Healthcare

The medical sector was an early user of 3D printing due to its customization and personalization possibilities and its capacity to improve people's lives as procedures improve and medical-grade materials are created. Examples include metal casting of dental crowns and tools over which plastic is vacuum moulded to make dental aligners. The technology is also used to manufacture hip and knee implants, hearing aids, orthotic insoles for shoes, personalized prosthetics, and implants for patients with special needs.

Surgical guides that are 3D-printed are also helping surgeons treat patients through the healing phases. Figure 3.15 shows a 3D printed upper and lower jaw.



Figure 3.15: Upper and lower jaw printed on a 3D printer



Robotics

3D printing technologies have been widely adopted in robotics due to their ability to create custom parts quickly and easily, allowing for faster prototyping and greater customization. These technologies enable the production of lightweight and intricate shapes, resulting in more complex and agile robotic systems with improved performance. Figure 3.16 shows a 3D printed robotic arm performing an automated task at a production line.



Aerospace and Automobiles

In aircraft development, standards are strict, and industrial 3D printing technologies are used extensively to create precise parts and tools. Due to process and material developments, some non-critical parts are already flying on aircraft. Many automakers followed the aerospace industry's path as shown in figure 3.17. First, employing the technology for prototyping, then developing and adapting their manufacturing procedures for automotive parts. Many automakers are looking at 3D printing to produce spare and replacement components on demand rather than storing massive inventory.

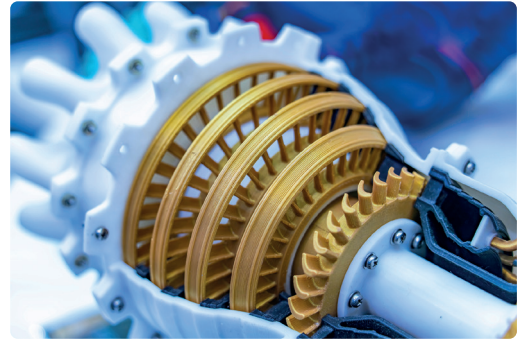


Figure 3.17: Jet engine printed model metal plastic

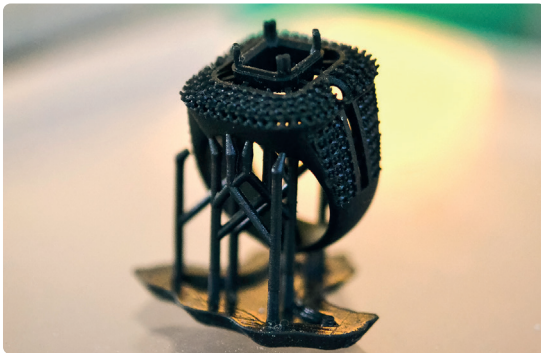


Figure 3.18: Ring photopolymer printed on a 3d printer

Jewelry

Traditional jewelry design and production require high levels of expertise and understanding in fabrication, mould-making, casting, electroplating, forging, silver and gold smithing, stone-cutting, engraving, and polishing. Each of these fields has grown over time and demands technical understanding in jewelry making. 3D printing is changing the traditional methods of making jewelry. It has brought significant changes to the whole industry, from new design freedoms that are shown in figure 3.18 to improved traditional techniques to direct 3D printed production that eliminates several traditional phases.

Art

Artists and sculptors use 3D printing to explore form and function in new ways. Many artists have begun using 3D modeling, scanning, and printing. 3D scanning and printing also provide possibilities for allowing artists and students to reproduce the work of past masters and create accurate replicas of historical masterpieces as shown in figure 3.19.

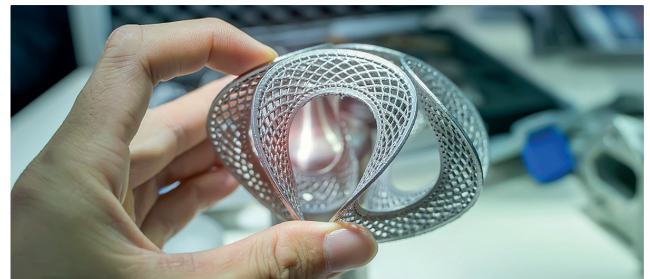


Figure 3.19: Piece of art printed on 3d printer

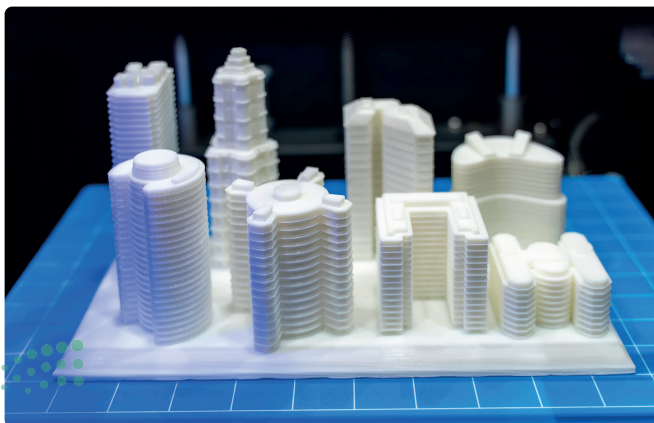


Figure 3.20: Architectural model printed in a 3D printer

Architecture

Three-dimensional printing has long been used to create accurate architectural models of an architect's vision. 3D printing is a fast, easy, and economically viable way to produce detailed models from architects' 3D CAD files and digital data. Many successful architectural businesses employ 3D printing to promote innovation and rapid prototyping as shown in figure 3.20.



Printing Process of a 3D Model

Printing your 3D model is an exciting moment in the design process. It's the stage where your virtual creation becomes a physical object you can hold and inspect. To get to this stage, you need to prepare your digital file for printing, which involves a number of steps. You will go through the process of exporting a FreeCAD file as a .obj file and then preparing it for printing using software to prepare the 3D model for printing. Let's open FreeCAD and load the 3D model that you have created in the previous unit to prepare it for printing.

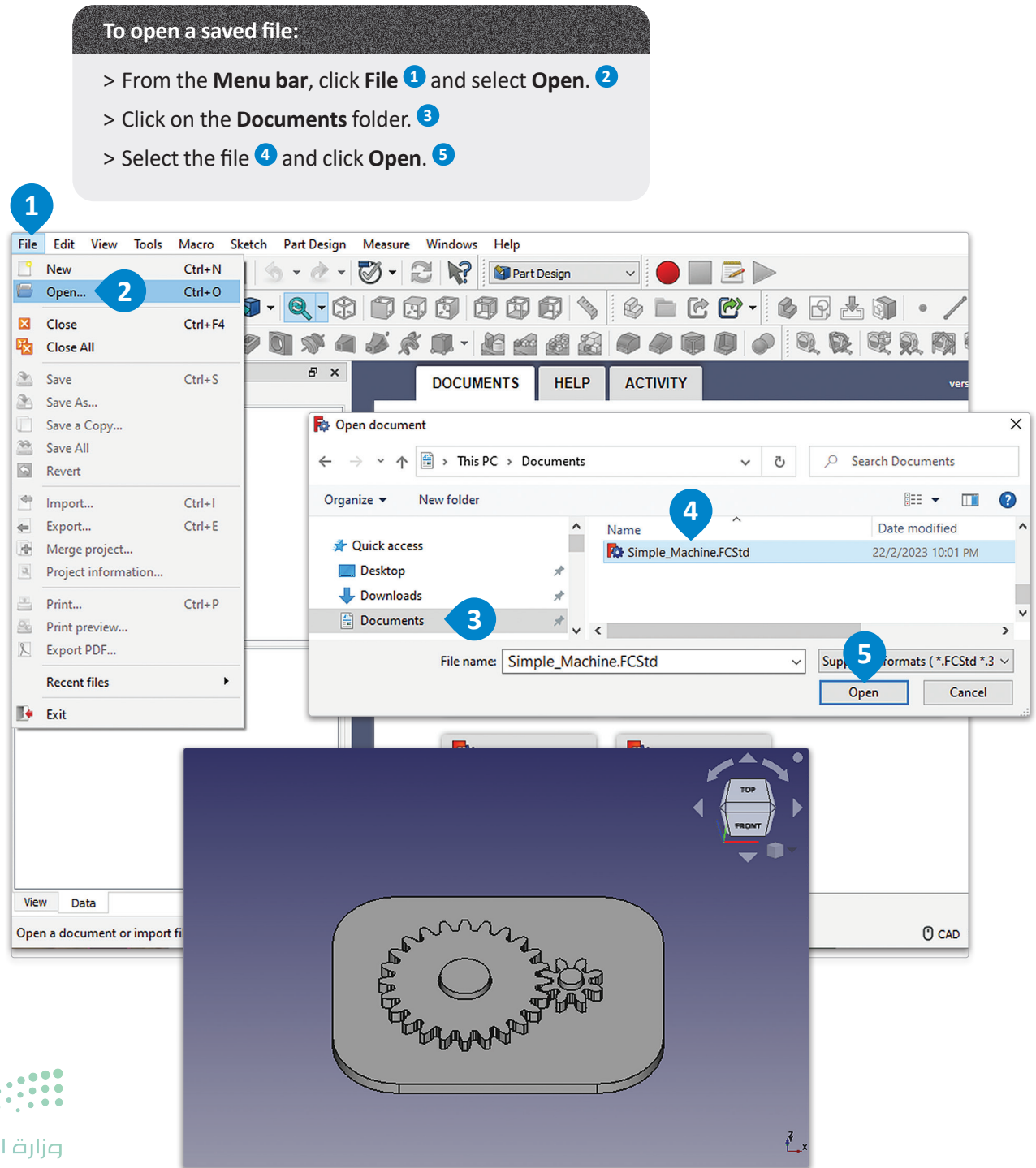


Figure 3.21: Opening a saved file

Exporting a File

To export a file from FreeCAD, you need to select the body (Small Gear) you want and then export it. The format you must export the file in, is OBJ or STL. Name the file and select the location where you want to save it. You can repeat this process for any additional bodies (Big Gear, Base) you want to export. Once you have exported all the bodies, you can import them into your slicing software, for example Ultimaker Cura, which prepare them for 3D printing.

To export a 3D model:

- > From the **Model** tab, double click to select the "**Small Gear**". **1**
- > From the **Menu bar**, click **File** **2** and select **Export**. **3**
- > Click on the **Documents** folder. **4**
- > Type a name **5** and in the **Save as type**: drop down menu, select **Alias Mesh (*.obj)**. **6**
- > Click **Save**. **7**

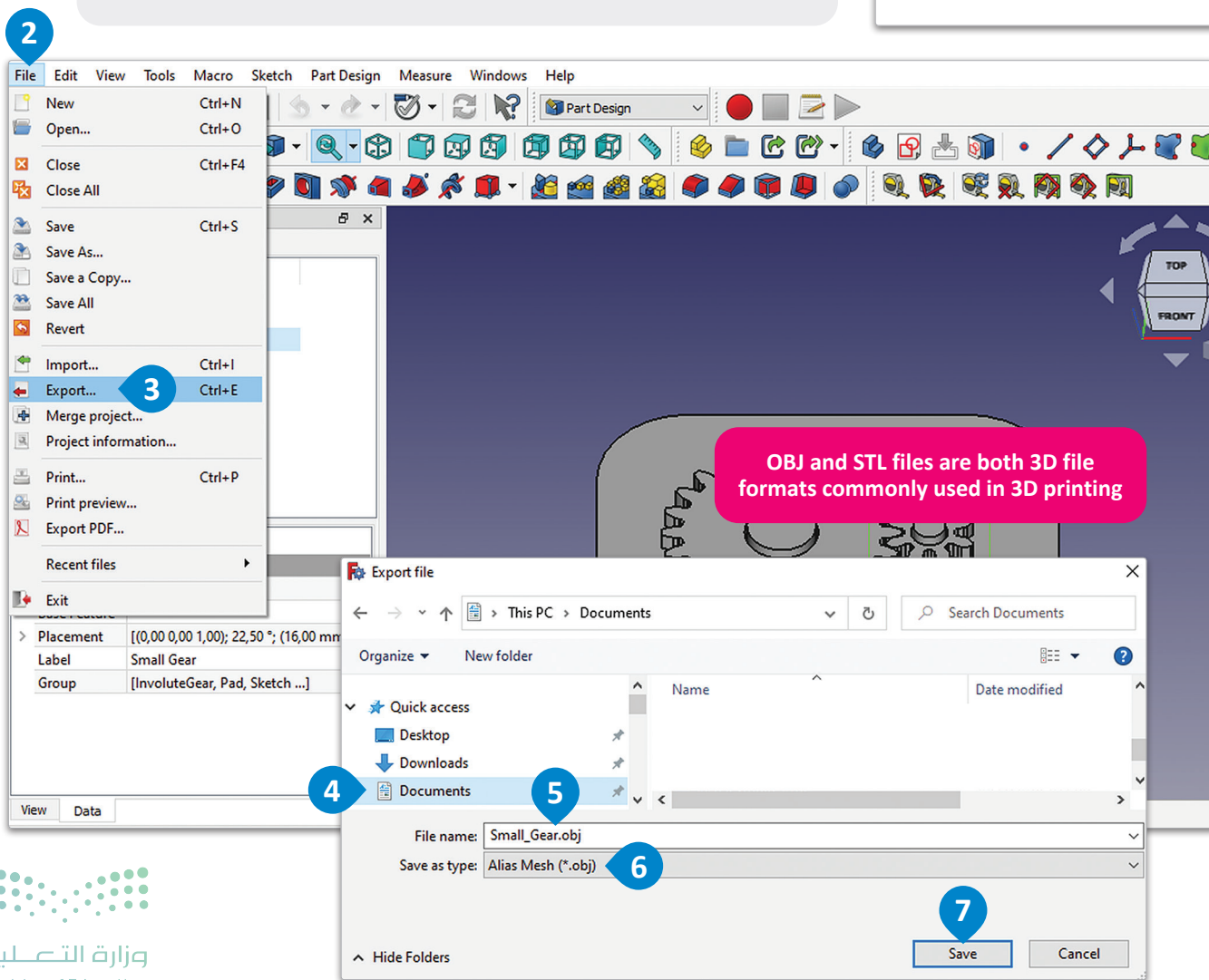
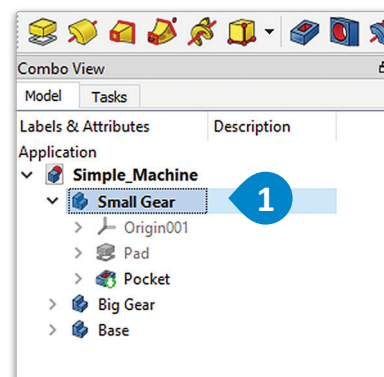


Figure 3.22: Exporting a 3D model

Use the same method to export the 3D models for the Big Gear and the Base as OBJ files.

Printing Software

Ultimaker Cura is free, open-source software used to prepare 3D models for printing. It allows you to customize and optimize settings such as print speed, quality, and support structures for a 3D printer. Ultimaker Cura is compatible with a wide range of 3D printers and provides a user-friendly interface for slicing and preparing 3D models for printing. You can download the Ultimaker Cura software from the following link:

Slicing software takes your 3D model and slices it into individual layers which the printer can then use to create the final object.

<https://github.com/Ultimaker/Cura/releases/download/5.3.1/UltiMaker-Cura-5.3.1-win64.exe>

Now that you have all three files exported in OBJ format, you can open the slicing software.

The menu bar includes File, Edit, View, Settings, Extensions, Preferences, and Help. These provide options for opening, saving, and editing files, configuring print settings, and accessing community resources.

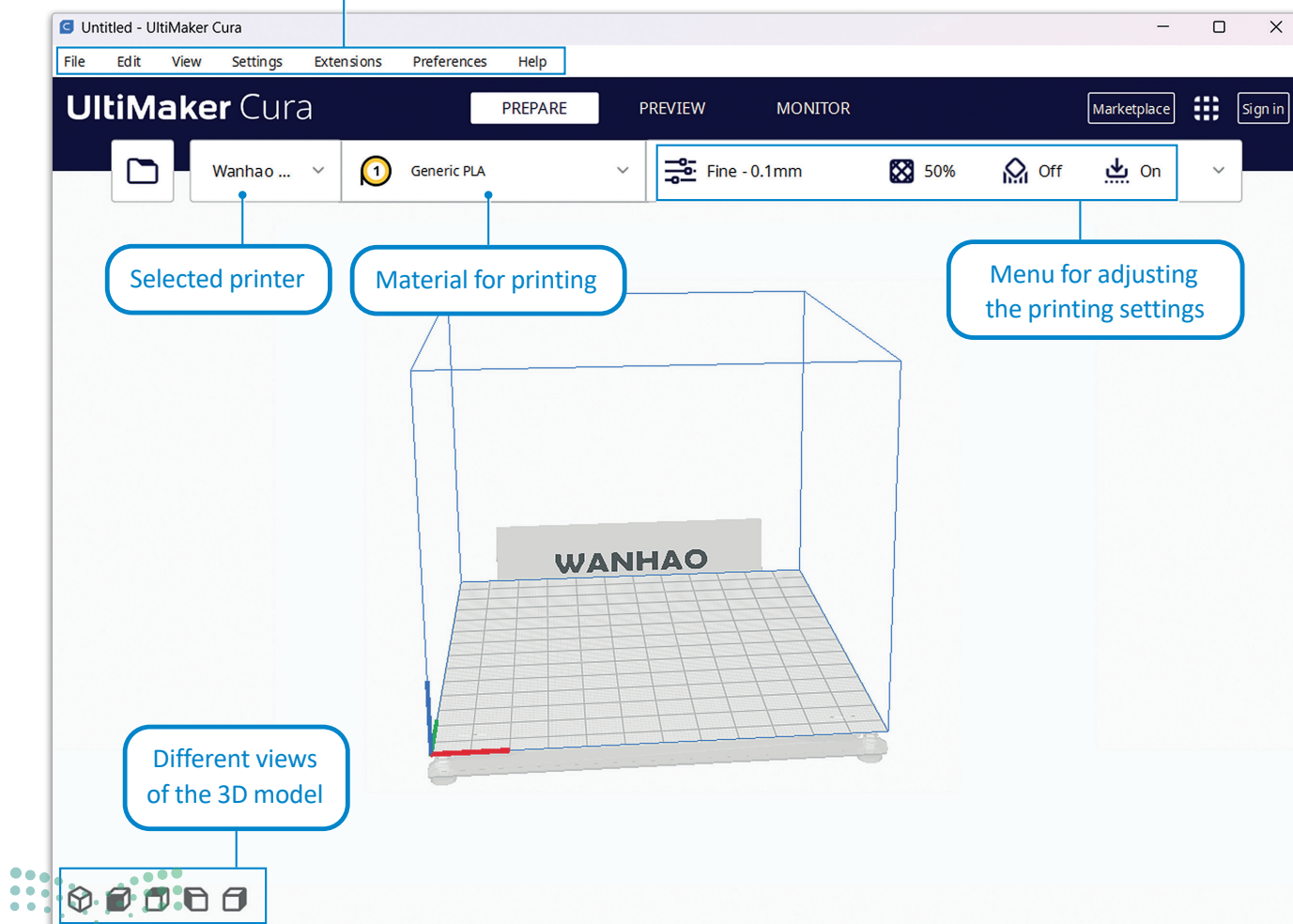
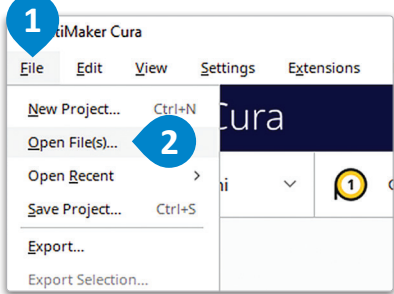


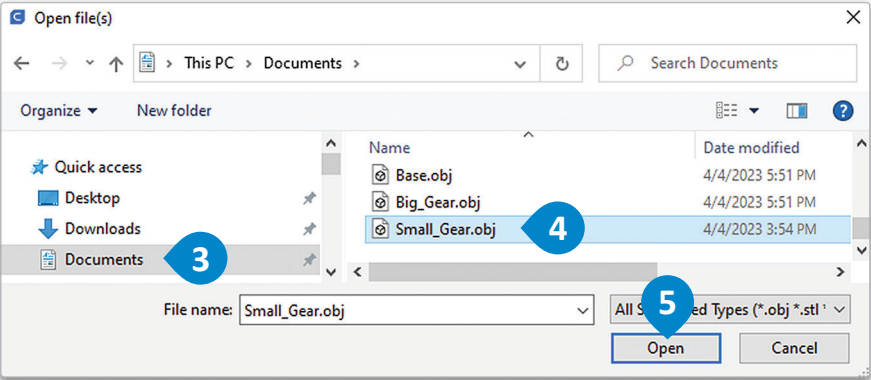
Figure 3.23: Ultimaker cura

Next open the Small Gear 3D model file.

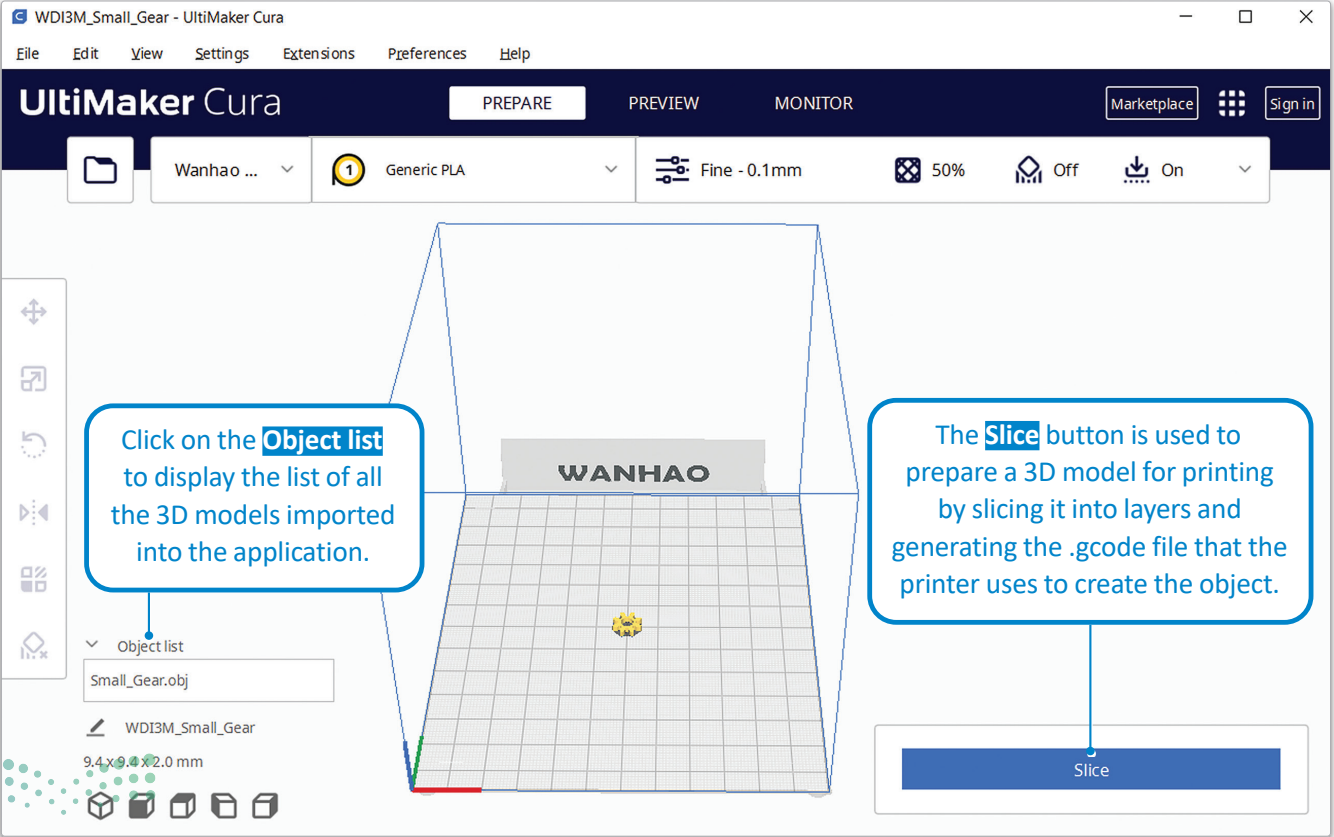
To open a .obj file:

- > From the **Menu bar**, click **File** 1 and select **Open File(s)....** 2
- > Click on the **Documents** folder 3 and select the file you want to open. 4
- > Click **Open**. 5





When you click on the slice button you can see the time that is needed for the 3D model to print.



Click on the **Object list** to display the list of all the 3D models imported into the application.

The **Slice** button is used to prepare a 3D model for printing by slicing it into layers and generating the .gcode file that the printer uses to create the object.

Figure 3.24: Opening a .obj file

Before adding the other two 3D models, let's take a look at the transformation tools and the navigation style in Cura.

When an object is selected, a menu appears with a variety of transformation tools that can be used to adjust the position, size, orientation, and appearance of the object. These tools include options to move, scale, rotate, mirror, and apply per-model settings, as well as a support blocker tool that allows users to selectively add or remove support structures for specific areas of the model.

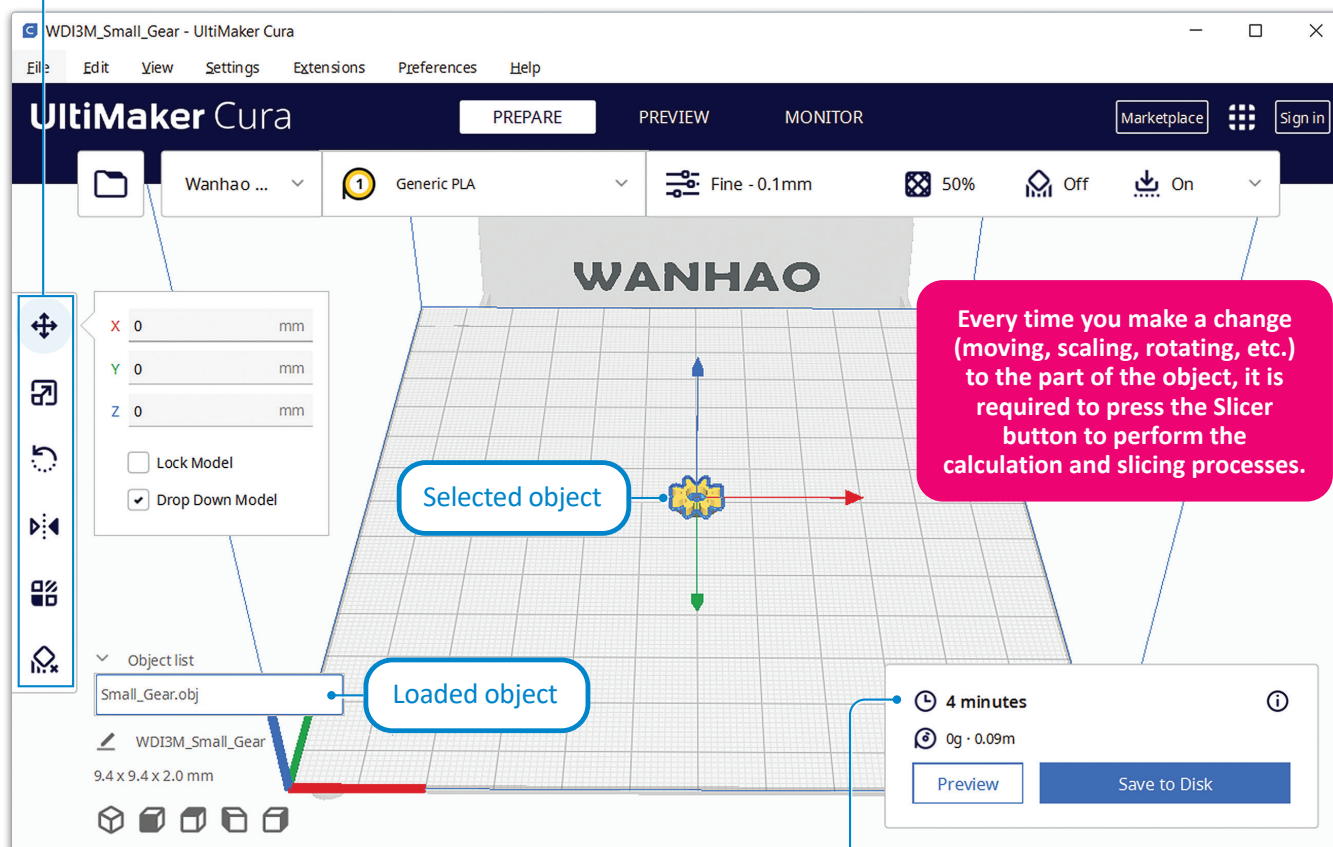


Figure 3.25: 8-tooth 3D model

The navigation style for interacting with and moving through a 3D model in Ultimaker Cura.



Select or
deselect objects



Zoom and pan
the view



Rotate
the view

Time needed
for printing

In order to fit the three 3D models on the build plate, you will need to use the transformation axis. The red arrow represents the X-axis, the green arrow represents the Y-axis, and the blue arrow represents the Z-axis. These arrows indicate the direction in which the object can be moved, as shown in figure 3.26.

Once you have added the three models and moved them in order to fit them onto the build plate, the result should be similar to figure 3.27 below.

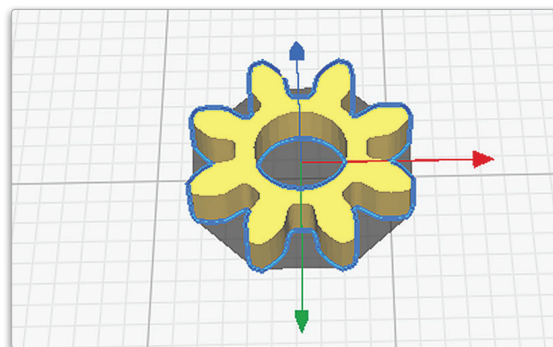


Figure 3.26: 8-tooth 3D model

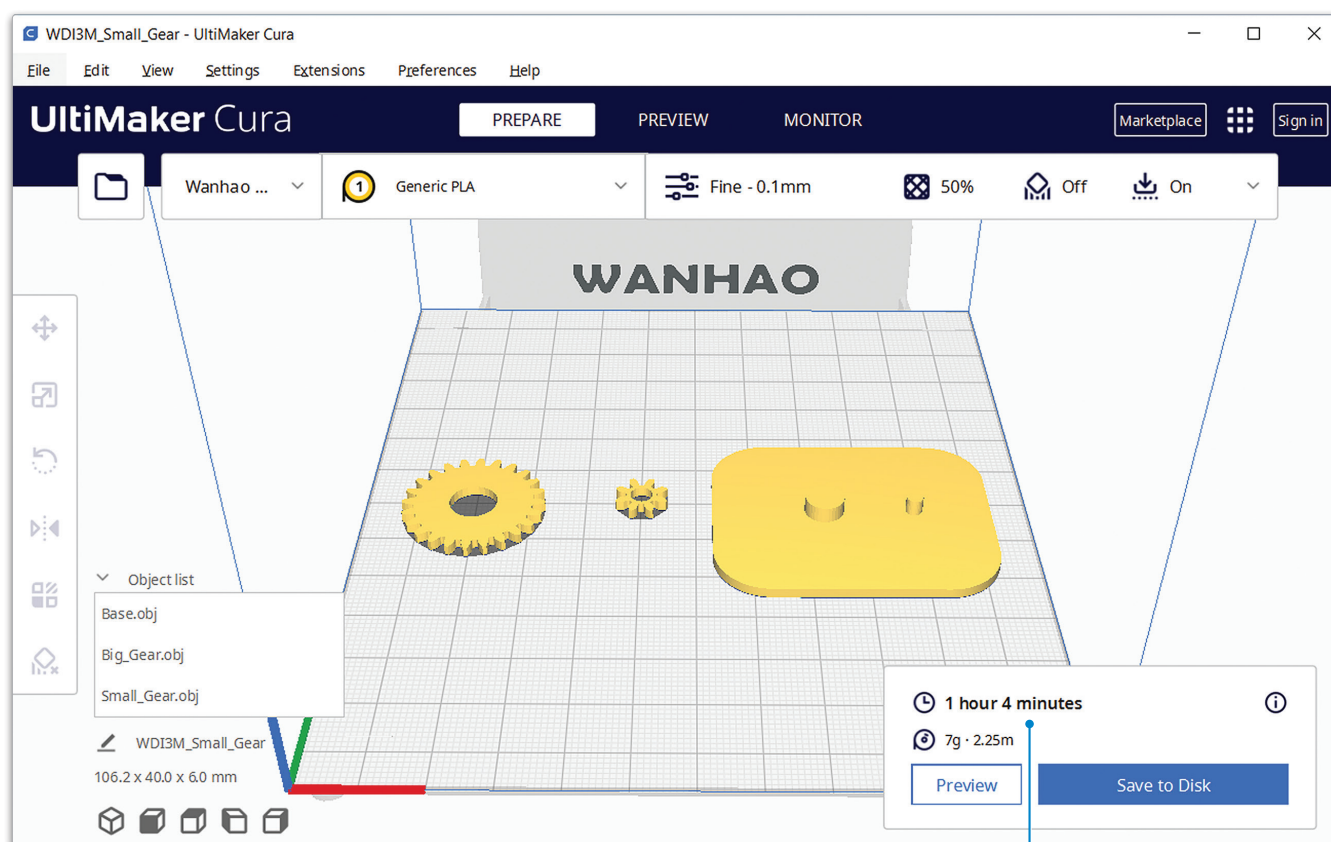


Figure 3.27: The three models on the build plate

When all three objects are added, and the slicer button is pressed you can see that the time has changed to **1 hour and 4 minutes**.

INFORMATION

The decision on whether to print objects separately or together depends on the size and complexity of the models and the printer's capabilities. Printing multiple objects simultaneously can save time and material, but it also increases the risk of print failure, especially if the models are large or require different settings.



Management Tools

The different colors in preview mode differentiate between different parts of the print. Usually, the cyan color indicates where support structures will be placed, the yellow color indicates the faces of the models, and the red color is used to highlight the edges. These colors help us to visualize the final result of the 3D print, making it easier to identify any potential issues or areas that require adjustment before printing. Let's take a look at Table 3.3 to get a better understanding of the different printing management tools.

Table 3.3: Printing Management Tools

Name	Properties
PREPARE	Allows you to adjust print settings, manage print profiles, and slice 3D models into G-code files that your printer can understand.
PREVIEW	Allows you to view a 3D representation of your sliced model, together with the support structures, and to check for any potential printing issues.
MONITOR	Provides real-time information about your ongoing print, such as print condition, estimated time remaining, and any errors that may occur. Monitor function is only available once the 3D printer is connected via USB/WiFi/Bluetooth connection/cable.

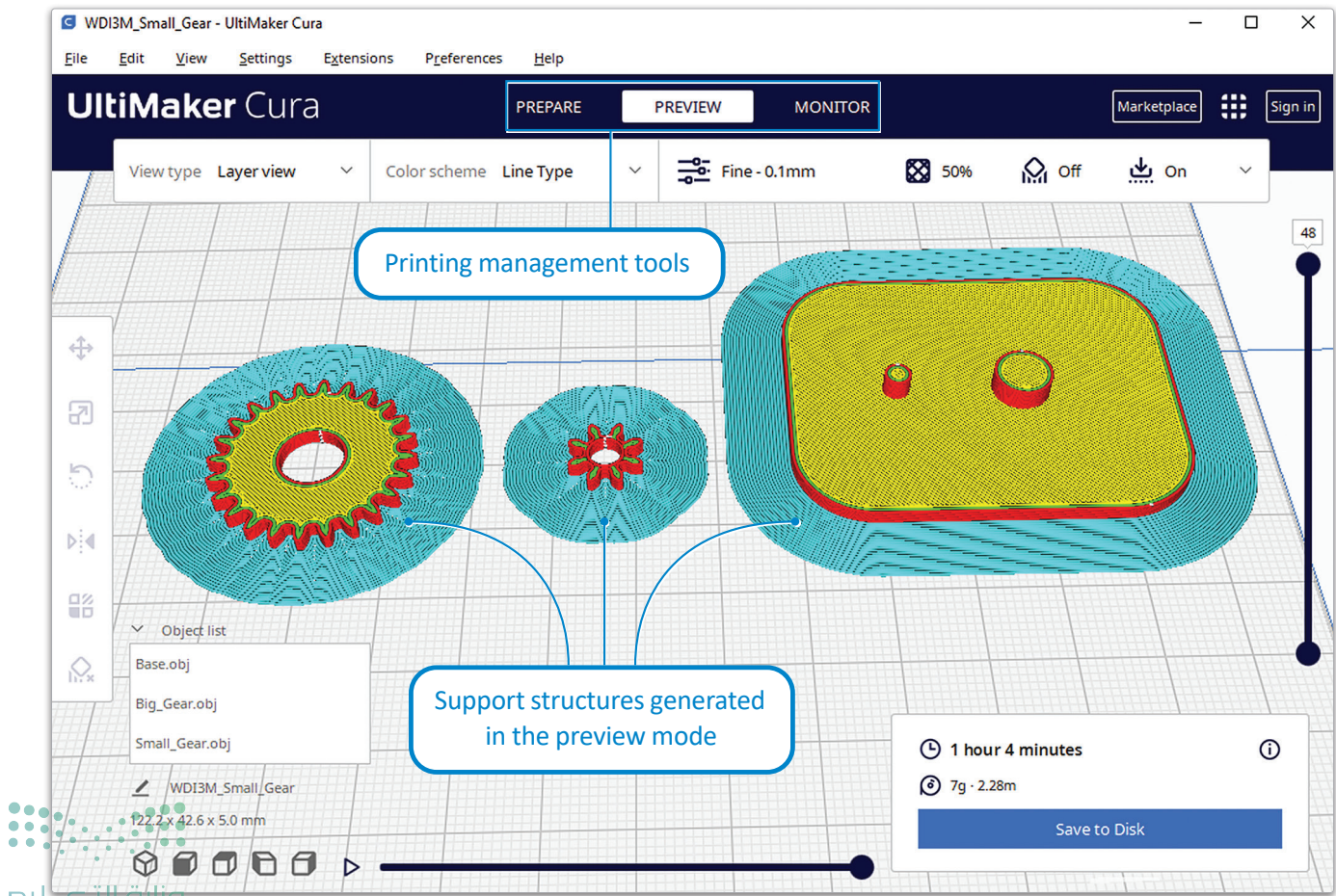


Figure 3.28: Preview mode

Finally, you will save your project in .gcode format in order for your printer be able to print the 3D models.

Create the file for printing:

- > Click on the **Slice** button. **1**
- > From the **Menu bar**, click **File** **2** and select **Export....** **3**
- > Click on the **Documents** folder. **4**
- > Type a name. **5**
- > In the **Save as type:** drop-down menu, select **G-code file (*.gcode)**, **6** and click **Save.** **7**

A .gcode file is a plain-text file that contains instructions for a printer in order to create a 3D object.

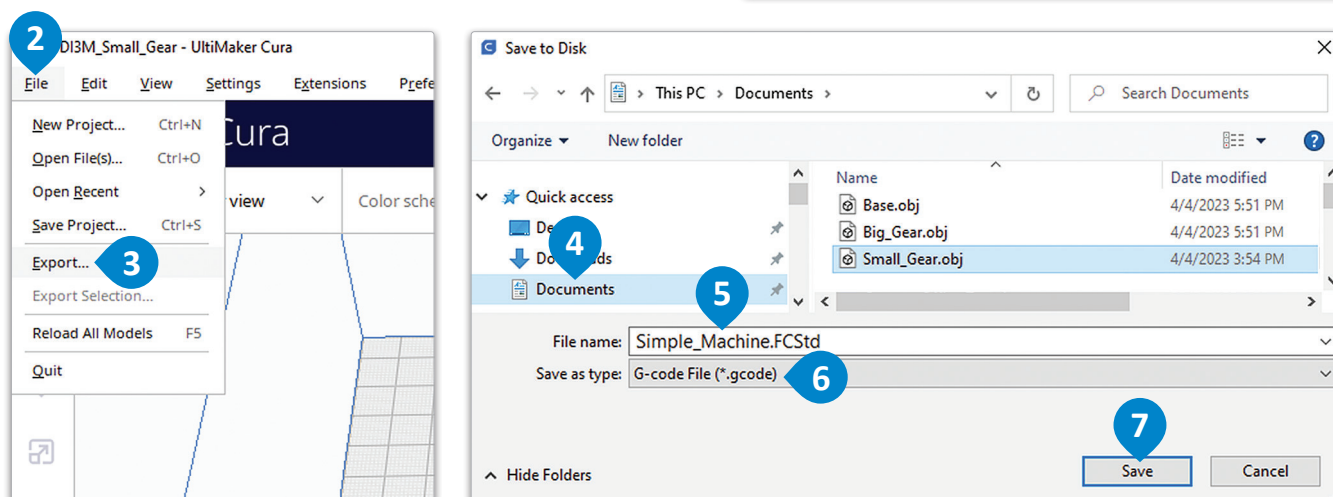
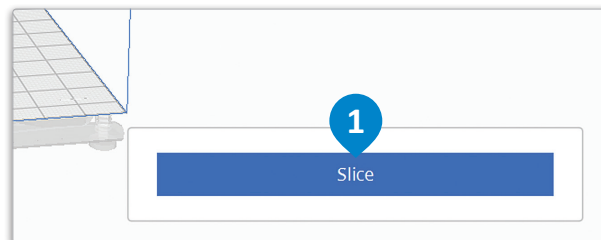


Figure 3.29: Creating the file for printing

Other export options that you can use for printing are the OBJ and STL file formats.

- OBJ (or .obj) stands for "Object" and is a file format that stores 3D model data, including geometry, texture information, and other material properties. It is a widely used file format and is supported by many 3D software applications.
- STL (or .stl) stands for "Stereolithography" and is a file format that contains only the surface geometry of a 3D model, represented by a collection of connected triangles. It is commonly used for 3D printing, as it provides a simplified model that can be used to generate a physical object layer by layer.

INFORMATION

An important aspect to consider when working with 3D printing is the compatibility of file formats. Different 3D printers and slicing software may support different file formats, and it's important to choose the right one to avoid compatibility issues. Common file formats for 3D printing include STL and OBJ, which are widely supported by most printers and slicing software.



Now that you have the .gcode file, you need to transfer it from your computer to your 3D printer. You can connect your computer to the printer via a USB cable or by transferring the file to an SD card and inserting it into the printer. Once the file is transferred, you can use the printer's interface to select the file and start the printing.

During printing, it is important to monitor the progress of the print and ensure that the printer is functioning properly.



Figure 3.30: Printed models



Figure 3.31: Assembled printed models

Let's take a look at Table 3.4 to get a better understanding of some common practices for operating a 3D printer:

Table 3.4: Useful tips for printing

Tip	Description
Level the build plate	A level build plate is critical for a successful 3D print. Make sure the build plate is leveled properly before starting any print.
Monitor the print	Keep an eye on the print progress to ensure that it is going smoothly. Check for any issues such as warping, layer shifting, or filament jams that may require intervention.
Clean the print bed	Ensure the build plate is clean and free of any debris, fingerprints, or oils before printing. This will help prevent adhesion issues and ensure a smooth surface finish.
Use the right filament	Use the appropriate filament for the print job. Different materials require different settings and temperatures.
Adjust print settings	Modify the print settings to achieve the desired result. This includes adjusting the layer height, print speed, and temperature.
Calibrate the printer	Regularly calibrate the printer to ensure accurate prints. This includes calibrating the extruder, bed, and axis.
Proper ventilation	Use the printer in a well-ventilated area to avoid inhaling any fumes emitted during the printing process.
Store filament properly	Store filament in a cool and dry place to prevent moisture absorption, which can lead to poor print quality.
Use support structures	Use support structures for overhangs or complex geometries to ensure successful prints.
Practice good maintenance	Regularly clean and maintain the printer to ensure its longevity and optimal performance.

Printing Settings

Cura is a popular software application used for 3D printing, and it has several advanced printing settings that can be adjusted to achieve the desired printing results.

Let's take a look at some details about the recommended print settings for Cura. In Table 3.5 you can see the different resolution options available and their properties.

Table 3.5: Cura resolution settings

Setting	Description
Extra Fine	This resolution produces the highest quality prints, with a layer height of 0.06 mm. However, it also takes the longest time to print.
Fine	This resolution produces high-quality prints with a layer height of 0.1 mm.
Normal	This resolution is the default setting in Ultimaker Cura, with a layer height of 0.15 mm. It produces good quality prints with a reasonable printing time.
Draft	This resolution produces prints with a layer height of 0.2 mm, making it faster to print but with lower quality.
Extra Fast	This resolution produces the very fast prints with a layer height of 0.3 mm. However, the quality of the print is compromised.
Coarse	This resolution produces prints with a layer height of 0.4 mm, making it even faster to print, but with lower quality than the other options.
Extra Coarse	This resolution produces the fastest prints with a layer height of 0.6 mm. This option is only suitable for prints that do not require fine details.

Extra Fine - 0.06mm

Fine - 0.1mm

Normal - 0.15mm

Draft - 0.2mm

Extra Fast - 0.3mm

Coarse - 0.4mm

Extra Coarse - 0.6mm



The resolution in Cura refers to the layer height of the 3D printed object. The layer height determines the quality and precision of the printed object, as well as the time it takes to print.

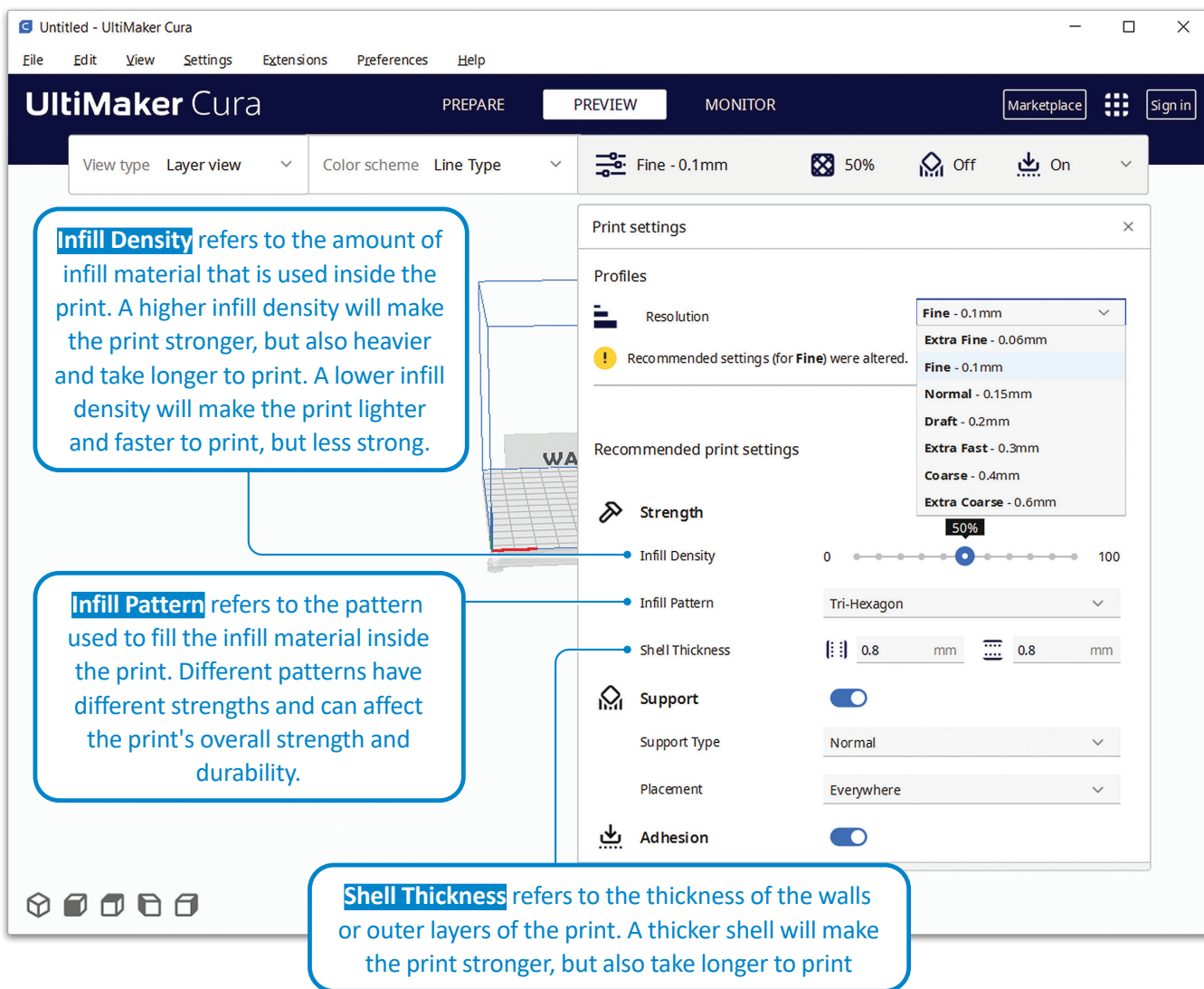


Figure 3.32: Print settings

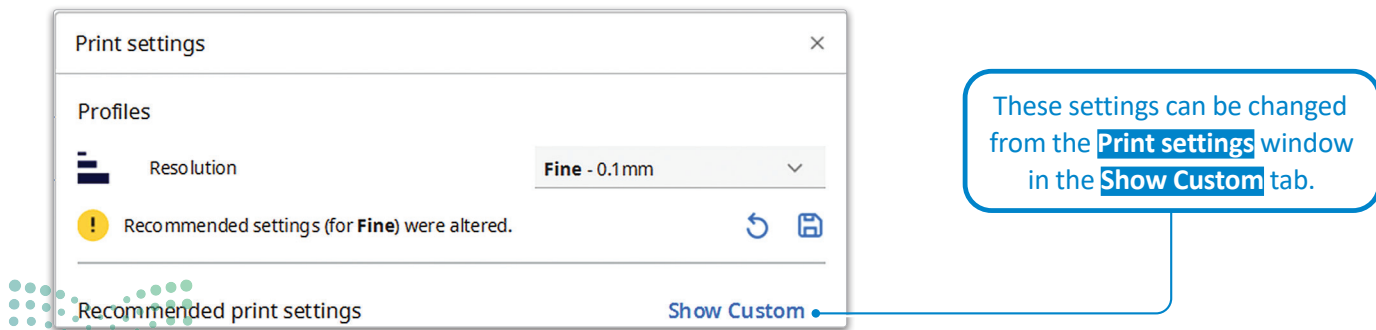


Figure 3.33: Custom settings

Let's take a look at Table 3.6 to understand some custom settings.

Table 3.6: Custom settings

Setting	Description
Quality	This setting determines the overall quality of the print, with higher quality settings producing finer details and smoother surfaces. It includes settings such as layer height, initial layer thickness, and line width.
Walls	This setting determines the number of walls, or shells, that will be printed around the perimeter of the object. It affects the strength and durability of the print, with more walls providing greater strength.
Top/Bottom	This setting determines the thickness and pattern of the top and bottom layers of the print. It affects the flatness and smoothness of the top and bottom surfaces.
Infill	This setting determines the density and pattern of the infill, or the interior structure of the print. It affects the strength, weight, and flexibility of the print.
Material	This setting determines the type of material that will be used for the print, such as PLA, ABS, or PETG. It affects the properties of the print, such as strength, flexibility, and temperature resistance.
Speed	This setting determines the speed at which the printer will move and extrude material during the print. It affects the overall print time and quality, with higher speeds producing faster prints but lower quality.
Travel	This setting determines the speed and path that the printer will use when moving between different parts of the print. It affects the overall print time and quality, with smoother travel producing better quality prints.
Cooling	This setting determines the fan speed and cooling time that will be used during the print. It affects the quality of the print, with better cooling reducing the risk of warping, stringing, and other defects.
Support	This setting determines whether or not support structures will be printed to support overhanging or complex features of the print. It affects the overall print time and quality, with more support structures providing better print quality but longer print times.
Build Plate Adhesion	This setting determines the type of adhesion that will be used to attach the print to the build plate, such as a brim, raft, or glue stick. It affects the overall print quality and the ability of the print to stay attached to the build plate during printing.
Dual Extrusion	This setting determines whether or not the printer will use multiple extruders to print different materials or colors at the same time. It affects the overall print time and quality, with dual extrusion producing more complex and colorful prints but also increasing the risk of print defects.



In Table 3.7, you can see some of the extra custom printing settings in Cura with brief explanations:

Table 3.7: Cura printing settings

Setting	Description
Quality	
Layer height	The layer height is the height of each layer that is printed. A smaller layer height can result in a smoother surface finish, but it can also increase print time.
Support	
Skirt	A skirt is a line of filament that is printed around the model but not attached to it. It helps to prime the extruder and ensure that the filament is flowing smoothly before printing the actual model.
Brim	A brim is a flat extension of the base of the model that helps to increase adhesion to the print bed. It is particularly useful for printing models with a small base that may not adhere well to the bed.
Raft	A raft is a printed base layer that sits between the model and the print bed. It provides additional support and adhesion, particularly for models with a large base or those that require a lot of support.
Infill	
Infill Density	Infill Density specifies the percentage of the internal volume of the object that will be filled with infill material, which can be plastic or another material. A higher percentage means a denser object with more infill, while a lower percentage means a lighter object with less infill.
Infill Pattern	The Infill Pattern determines the pattern in which the infill material will be laid down. The most common infill patterns are grid, lines, and triangles, but there are other patterns available as well. The choice of infill pattern can affect the strength, flexibility, and overall quality of the finished print.
Material Jetting	
Print speed	Print speed refers to the speed at which the printer moves during printing. A faster print speed can reduce print time, but it can also increase the risk of errors or inaccuracies in the final print.

These settings can be adjusted based on the specific requirements of the model being printed and can help to improve print quality, reduce printing time, and save material costs.

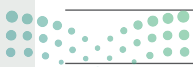
Exercises

1

Read the sentences and tick ✓ True or False.	True	False
1. 3D models can only be created with CAD tools.	☐	☐
2. 3D printers can only work on the X-Y axes.	☐	☐
3. 3D printers minimize the risk of human error.	☐	☐
4. SLA printing cures the liquid resin with a laser beam.	☐	☐
5. Laser sintering uses powder as a base material.	☐	☐
6. Paper is used in 3D printers as a base material.	☐	☐
7. Living human tissue cannot be 3D printed.	☐	☐
8. 3D printed objects have a smaller carbon footprint than traditionally manufactured objects.	☐	☐
9. 3D printed objects cannot be used for replacement parts.	☐	☐
10. 3D printers can be used to reconstruct old works of art.	☐	☐

2

Define 3D printing and describe how it impacts the work of engineers and designers.



3 Analyze the main differences between SLA and DLP printers.

This image shows a blank sheet of white paper with horizontal ruling lines. The lines are evenly spaced and extend across the width of the page. There are no margins, text, or other markings on the paper.

4 Describe how using powder as a base material differs from using liquid resin.

This image shows a blank sheet of white paper with horizontal grey ruling lines. The lines are evenly spaced and run across the width of the page. In the bottom-left corner, there is a small cluster of approximately ten light-green circular dots of varying sizes, some overlapping each other. The rest of the page is completely empty.

5 Explain how an EBM printer works and why it is used heavily in industrial applications.

6 Analyze the various types of plastic materials used as base materials in 3D printing.

7 List the main benefits of 3D printing for both industrial and personal use.



8 Illustrate how processing metals differs from ceramics in 3D printing.

9 Describe how 3D printing is used to advance healthcare applications.

10 Discuss how the aerospace and automobile industries utilize 3D printing in various departments.





Design a Pill Box

A pill box is a small container used to store and dispense pills, depending on the days of the week. In this lesson, you will design and print a pill box using your 3D printer. The pill box will have a recess to insert a cap to secure the pills inside the containers. The days of the week will be distinguished using Braille numbers on the box as shown in figure 3.34.

You will be focusing on the prototyping phase of the design process, where designers produce initial prototype ideas that explore design possibilities and variations. By creating a detailed sketch using isometric drawing, you can figure out how the pillbox mechanism works and ensure that the geometry of its components is suitable for the manufacturing process. This will enable you to create an accurate visual representation of the product, and make the design process more efficient by preventing costly and time-consuming changes.

So, let's use isometric drawing to create a sketch to accurately capture the dimensions and proportions of the pill box and to serve as the foundation for your 3D model.

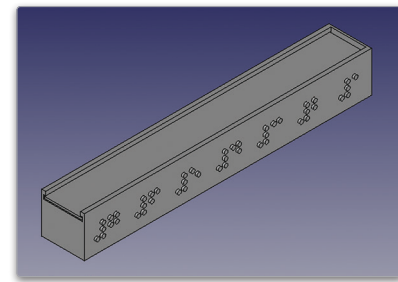


Figure 3.34: Pill box 3D model

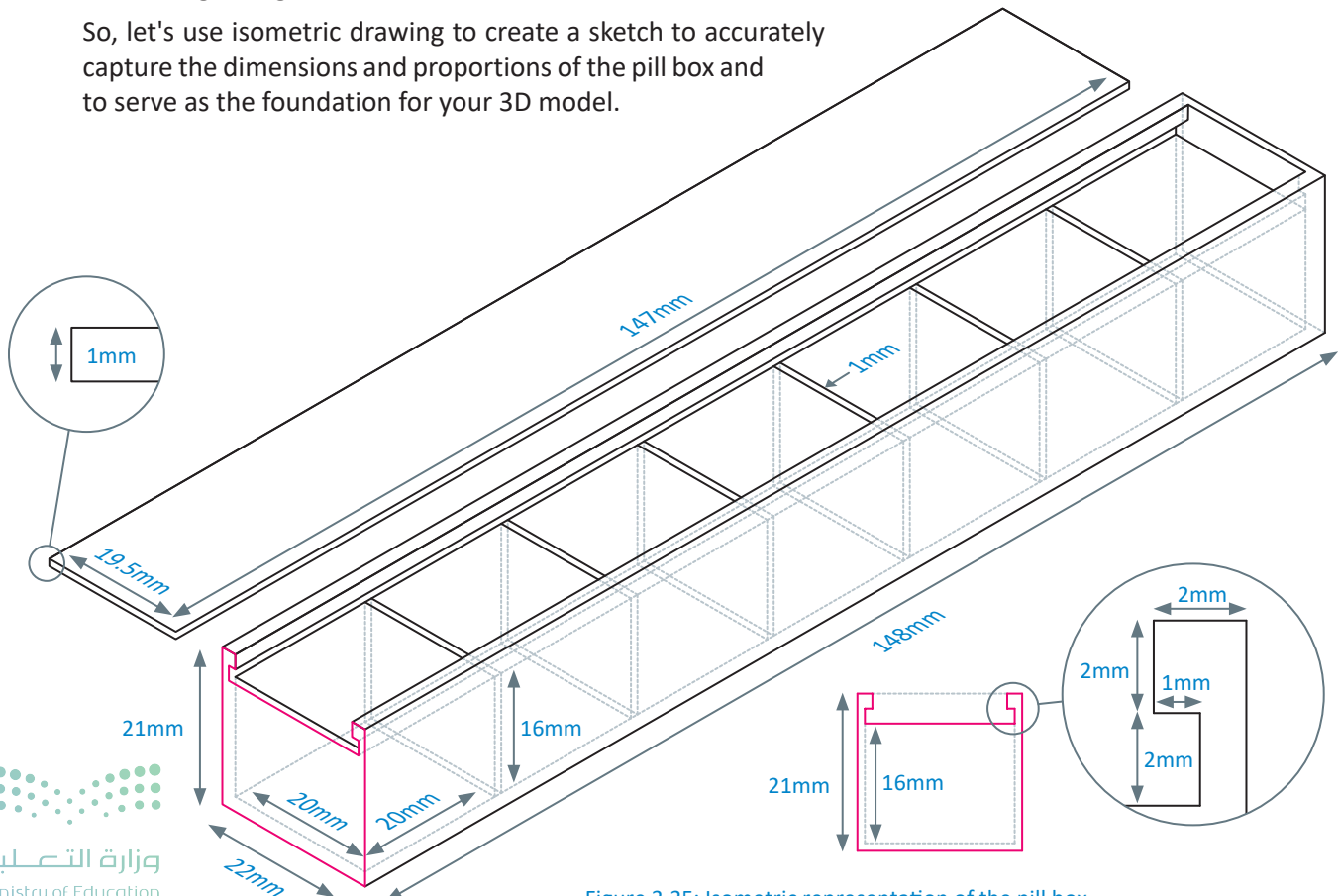


Figure 3.35: Isometric representation of the pill box

The pill box model will have two bodies:



The Pillbox-Body is a rectangular box designed to store and dispense pills for every day of the week. It has a length of 148 mm, a width of 21 mm, and is padded to a depth of 21 mm. The box has a recess at the top, where the cap will be inserted. The recess is made using a pocket 147 mm long. The Pillbox-Body has seven separate container boxes, each with dimensions of 20x20 mm and pocket depth of 16 mm. There is a separation of 1 mm between the containers, and each one has dots to indicate the numbers 1 to 7 for the days of the week, using the Braille system.

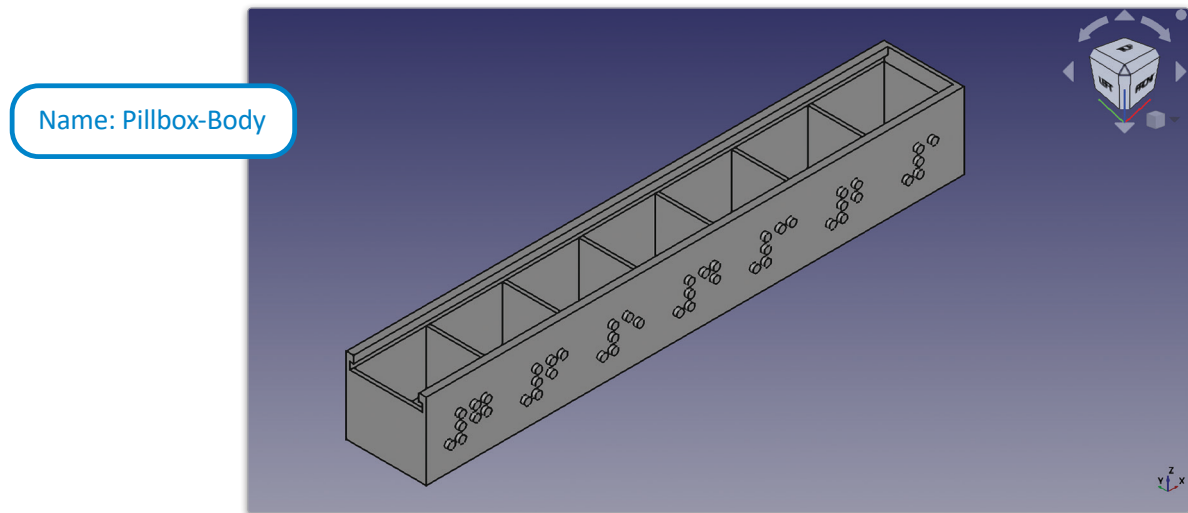


Figure 3.36: Pillbox-Body

The Pillbox-Cap is a cover designed to fit on top of the Pillbox-Body. It has a length of 147 mm, a width of 19.5 mm, and is padded to a depth of 1 mm. When the Pillbox-Cap is placed on top of the Pillbox-Body, it covers containers to keep the pills in place.

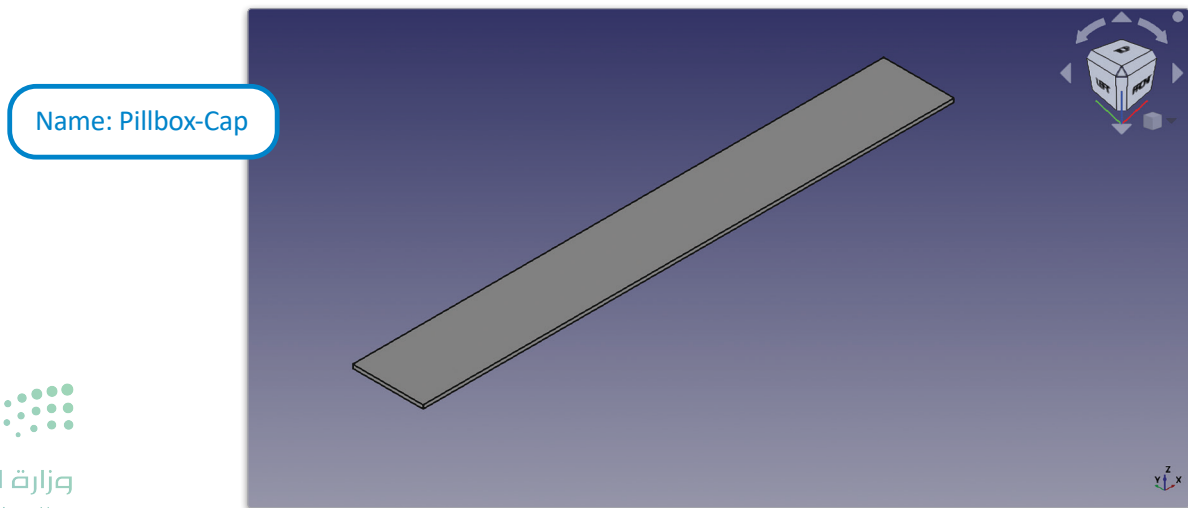


Figure 3.37: Pillbox-Cap

Let's start by creating the Pillbox-Body.

Design the Pillbox-Body

The Pillbox-Body is a container that will be divided into seven separate boxes for storing pills for each day of the week. The container will also feature dots that use the Braille system to indicate the numbers 1 to 7 for the days of the week. Let's create a new document to start designing your 3D model.

To create a new document:

- > Click on the icon "New" in the **toolbar**. **1**
- > From the **workbench drop-down menu**, select the "**Part Design**" workbench. **2**

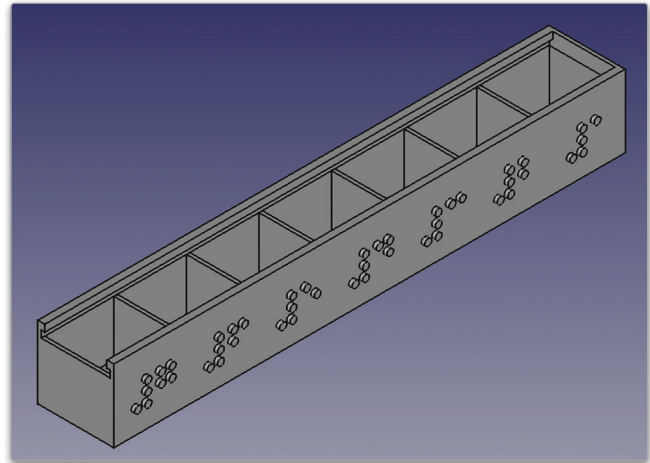


Figure 3.38: Pillbox-Body

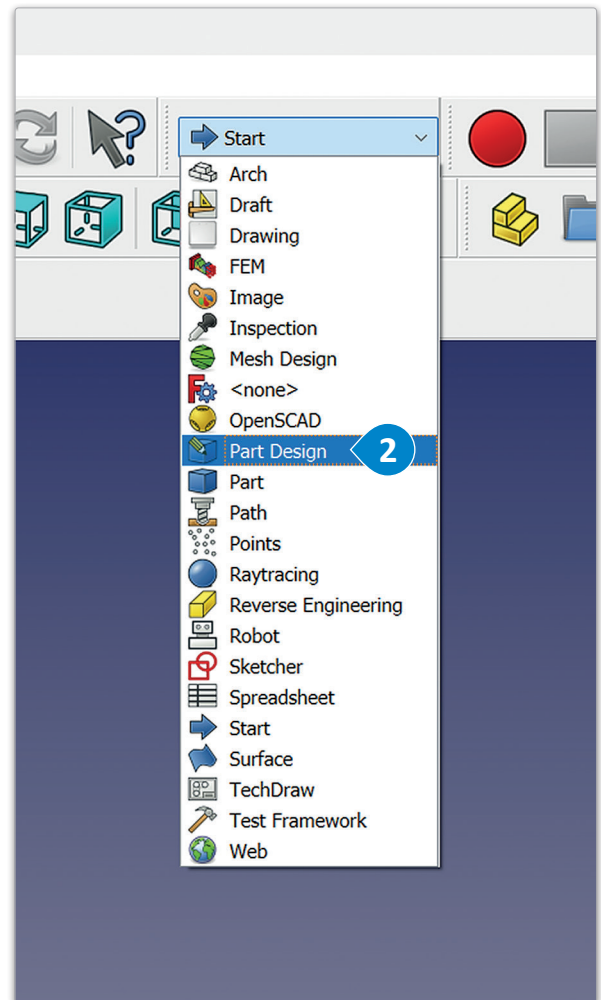
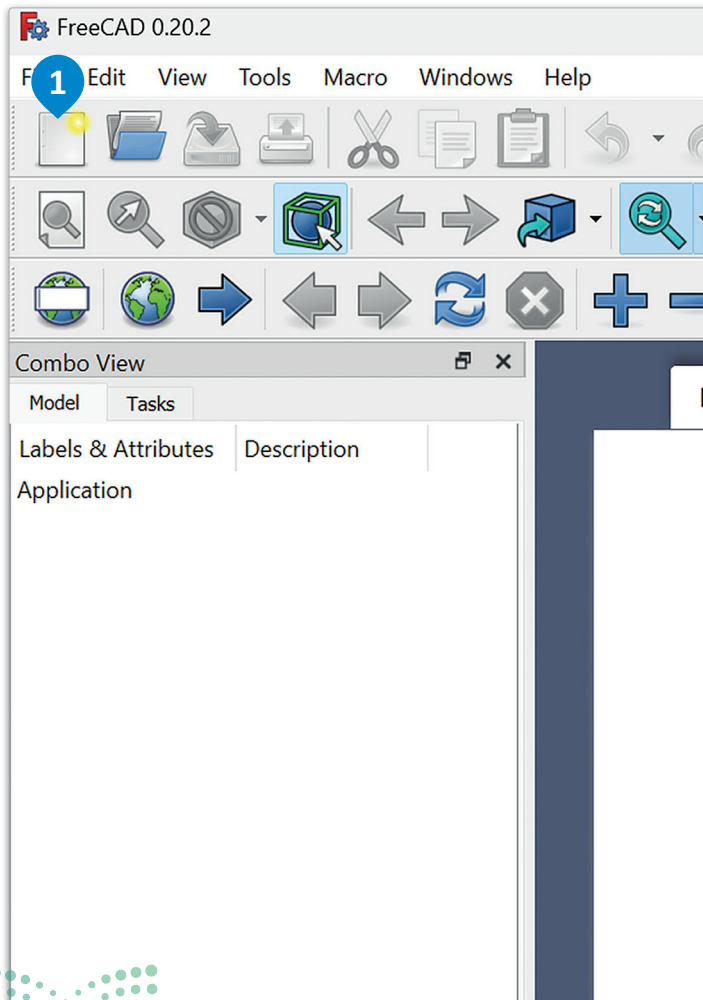


Figure 3.39: Creating a new document



Now you will create a body and name it Pillbox-Body.

To create Pillbox-body:

- > From the **toolbar**, click the **Create body** tool. ¹
- > From the **Data** tab, change the **Label** to **Pillbox-Body**. ²

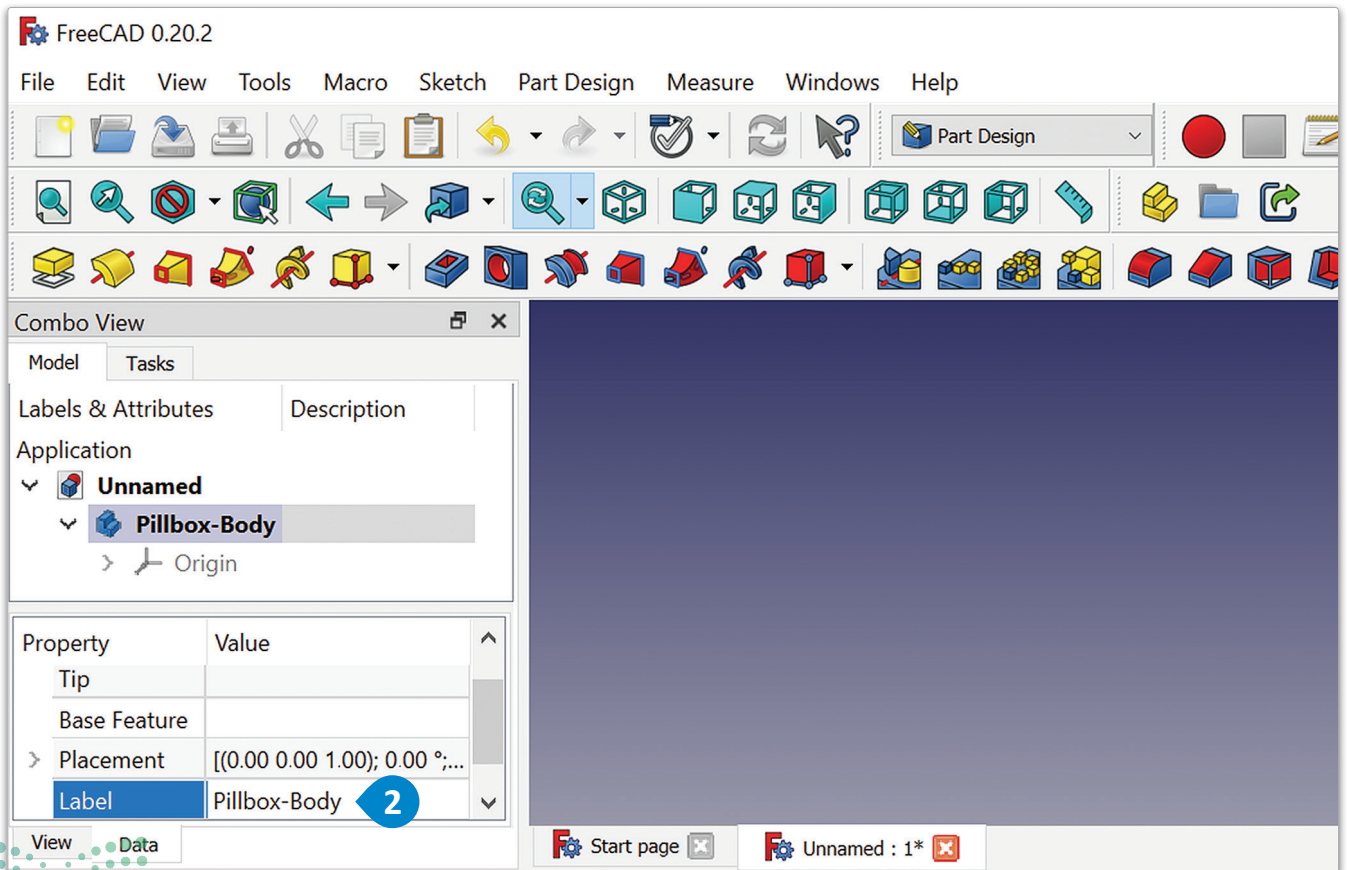
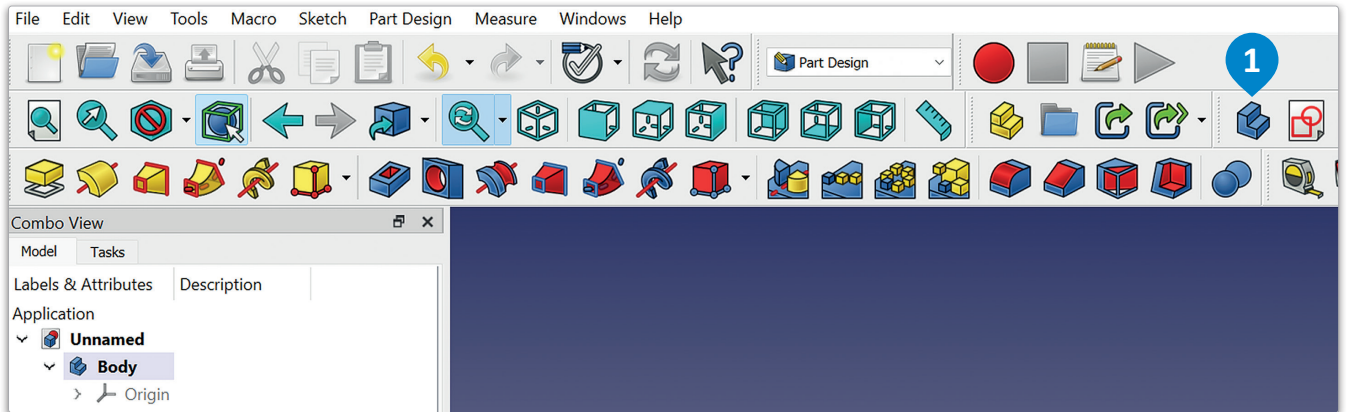


Figure 3.40: Creating Pillbox-body

Then create a new sketch and choose the XY plane.

To create a sketch and choose the XY plane:

- > From the **toolbar**, click the **Create sketch** tool. **1**
- > From the **Tasks** tab in the **Combo View**, click **XY_Plane**. **2**
- > From the **Tasks** tab in the **Combo View**, click **OK**. **3**

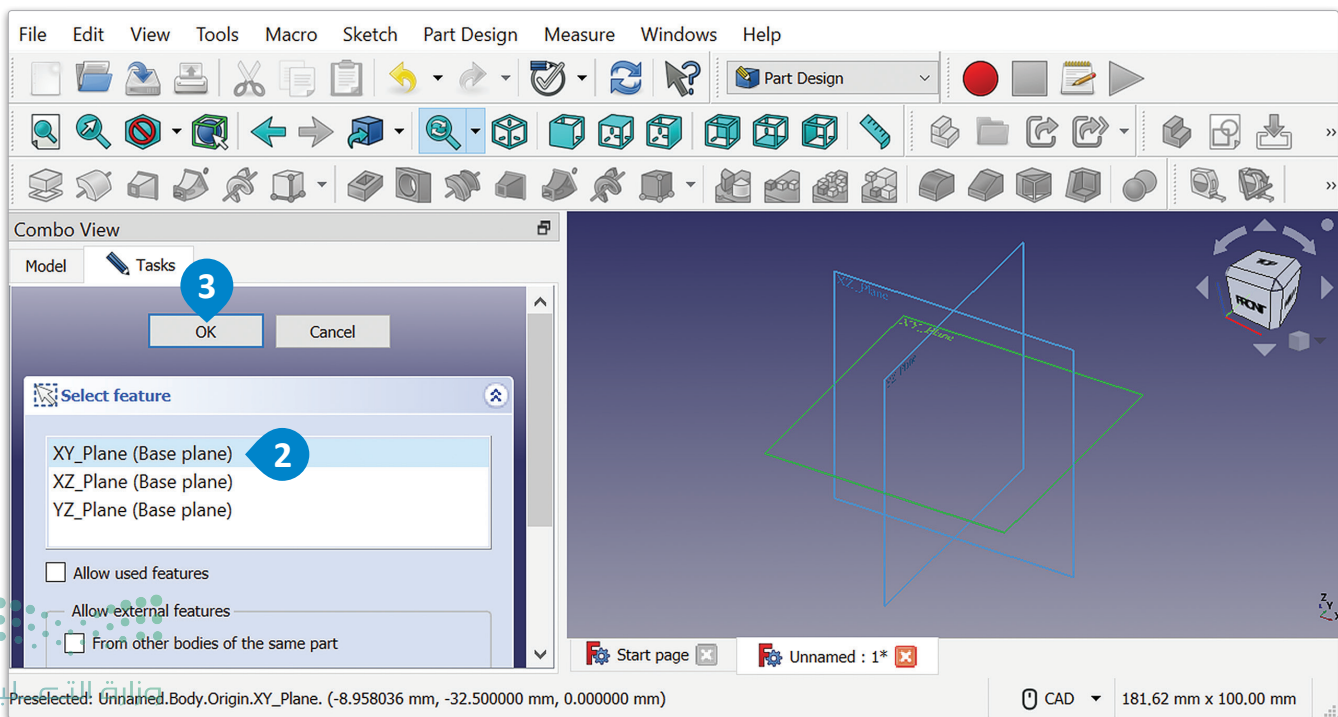
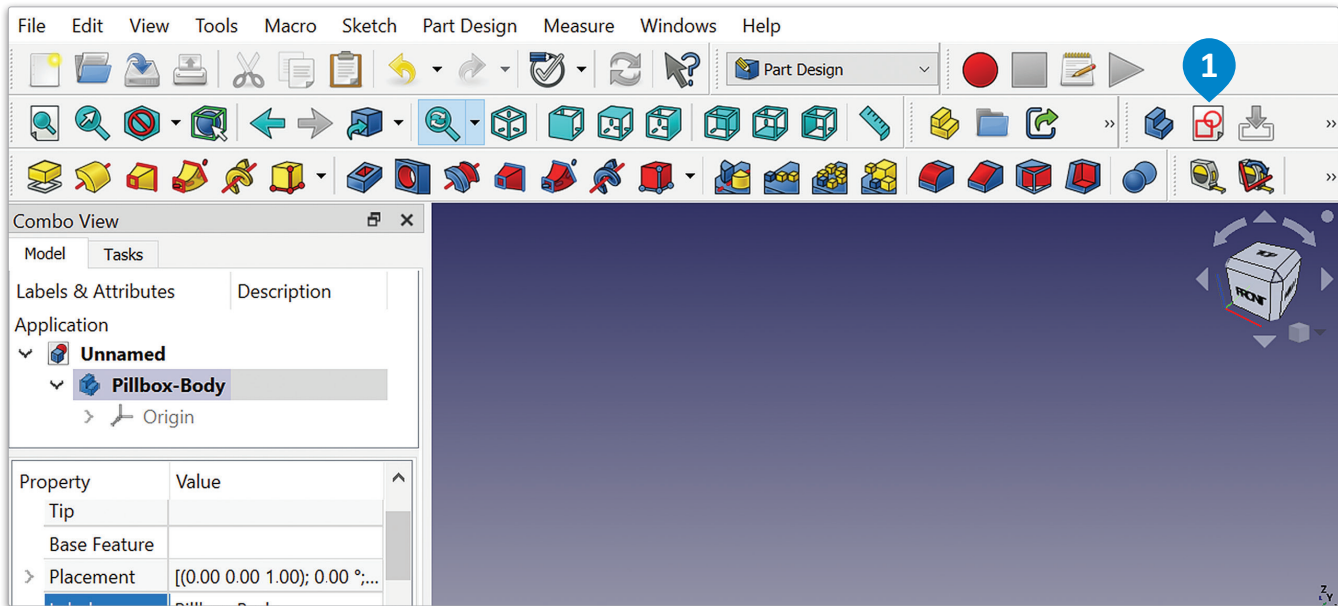


Figure 3.41: Creating a sketch and choosing the XY plane

Setting the grid to 1 mm is important because it allows for a more precise and accurate design. By using a smaller grid, you can create high resolution details that may be important for the functionality and aesthetics of the final product. It also helps to ensure that all parts are designed to the correct scale and proportions, which is essential for fitting the pieces together and creating a functional object.

To change grid size:

- > From the **Tasks** tab, click **Edit controls**. ¹
- > From the **Tasks** tab in the **Edit controls** tab, select **Show grid** ² and then select **Grid snap**. ³
- > From the **Tasks** tab, change the size of the grid to **1 mm**. ⁴
- > From the **Tasks** tab, click **Edit controls** to minimize the tab. ⁵

Working with a smaller grid can help you develop your design skills and attention to detail, which are important for any engineering or design project.

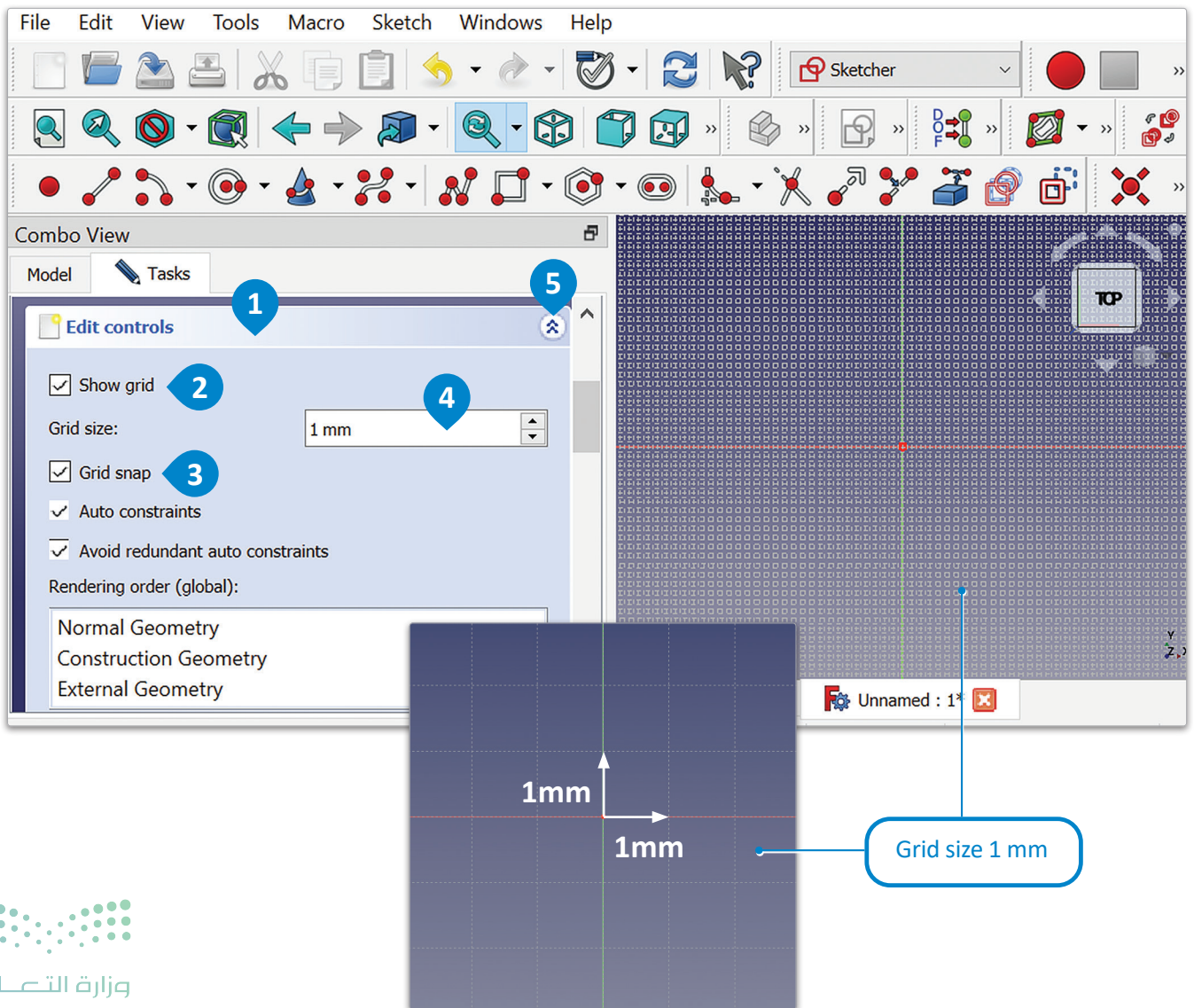


Figure 3.42: Changing the grid size

Next, use the rectangles tool to create a rectangle.

To create a rectangle:

- > From the **toolbar**, select the **Create rectangles** tool. **1**
- > Click on the sketch to set the first corner of the rectangle. **2**
- > Move the cursor to set the opposite corner of the rectangle, and click again to create the rectangle. **3**

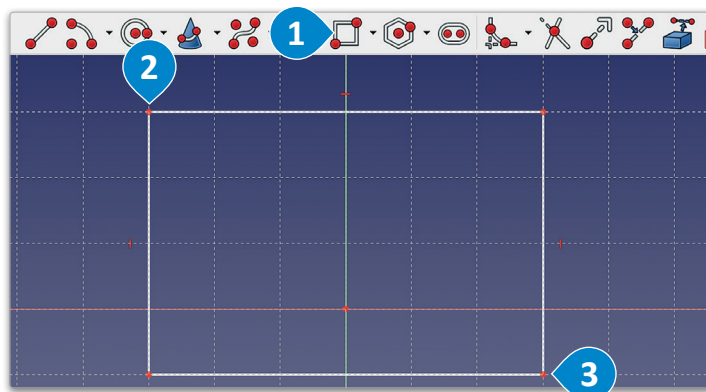


Figure 3.43: Create a rectangle:

Use constraints to set the rectangle a length to 148 mm and the width to 22 mm.

To constrain horizontal and vertical distance:

- > From the **Constraints toolbar**, select the **Constrain horizontal distance** tool. **1**
- > Click on the upper edge of the rectangle. **2**
- > Set the **Length** to **148 mm** **3** and click OK. **4**
- > From the **Constraints toolbar**, select the **Constrain vertical distance** tool. **5**
- > Click on the right edge of the rectangle. **6**
- > Set the **Length** to **22 mm** **7** and click OK. **8**

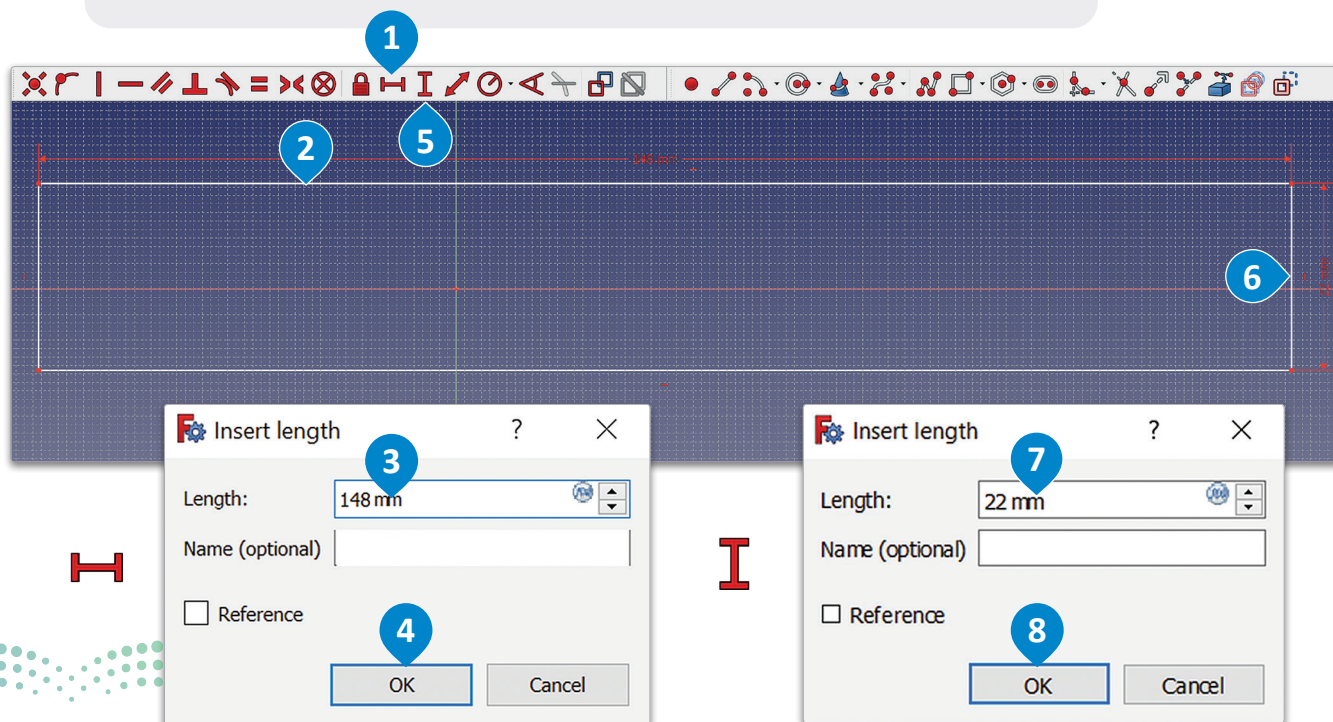


Figure 3.44: Constraining the horizontal and vertical distance

Constrain the position of the rectangle with respect to the axis.

To constrain points:

- > From the **toolbar**, select the **Constrain coincident** tool. **1**
- > Select the lower left corner of the rectangle **2** and then select the center of the axis. **3**
- > From the **Tasks** tab, click **Close**. **4**

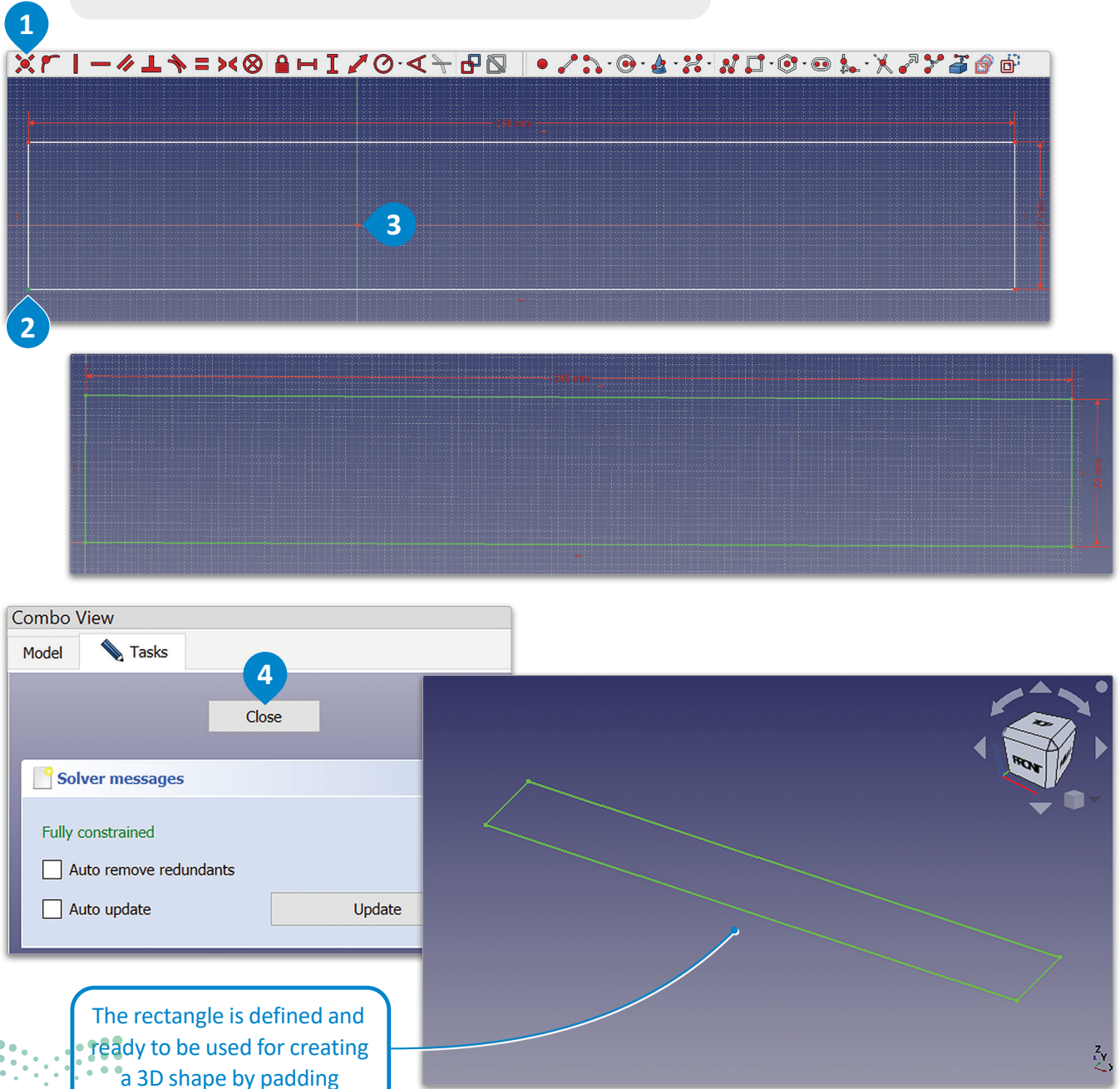


Figure 3.45: Constraining points

Use the Pad tool to extrude the rectangle into a 3D shape.

To create a 3D shape:

- > From the **toolbar**, click the **pad** tool. **1**
- > In the **Tasks** tab, change the length to **21 mm** **2** and click **OK**. **3**

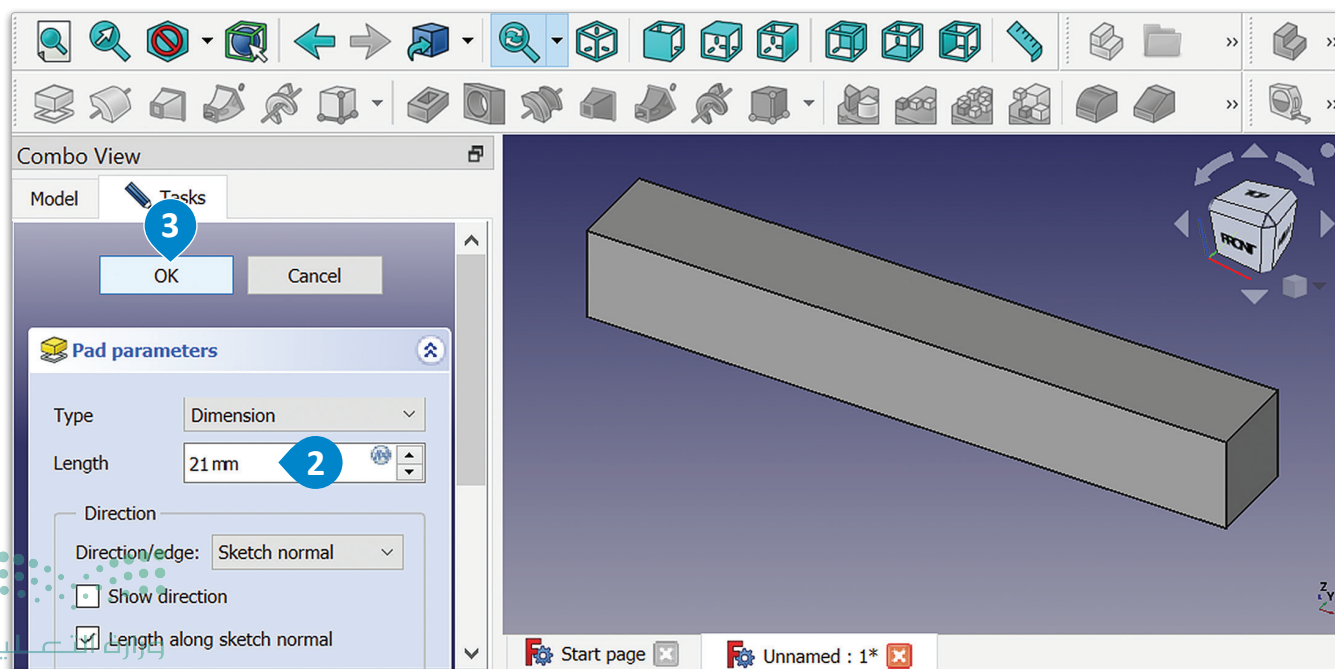
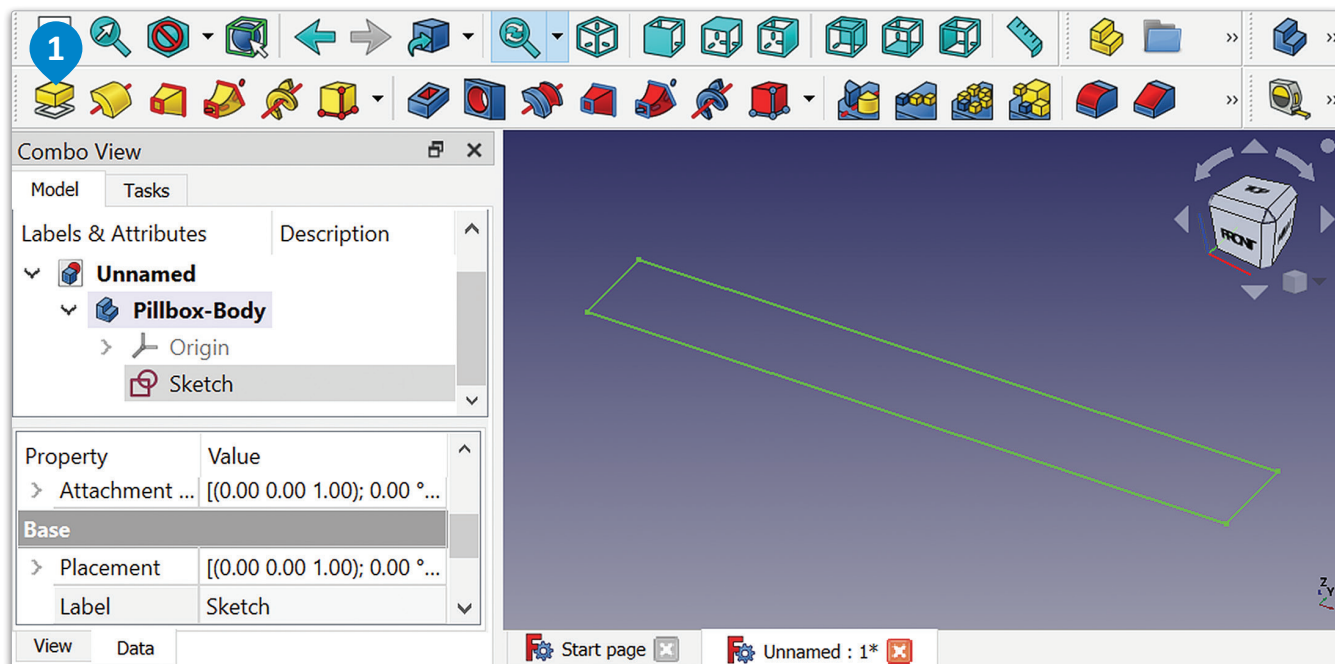
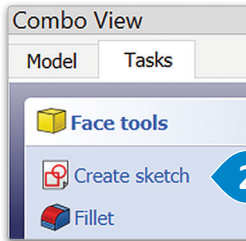
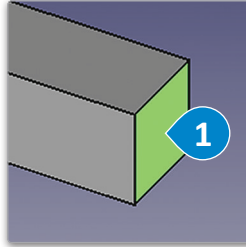


Figure 3.46: Creating a 3D shape

The polyline tool can be helpful when you want to create a series of connected line segments that form a closed shape. This tool can create complex sketches with many segments that can be edited and modified easily. You will use the polyline tool to create the shape of the recess on the top of the Pillbox-Body. Then you will use the pocket tool to cut out the shape and create the recess where the cap will be inserted. This pocket will have a depth of 1 mm, matching the thickness of the Pillbox-Cap.

To create a sketch on the top surface:

- > Click the **Pillbox-Body** to select its small, front surface. ①
- > From the **Face tools** in the **Tasks** tab, select the **Create sketch** tool. ②
- > From the **toolbar**, select the **Create polyline** tool. ③
- > Click on the sketch to set the first point of the shape and then create seven more points, like in the image. ④
- > From the **Tasks** tab, click **Close**. ⑤



When you create a new sketch, the software will create a new document for the sketch, and the settings for the document may not be the same as the settings for the previous document. Therefore, the grid size will not automatically carry over to the new sketch, and you will need to set it again manually.

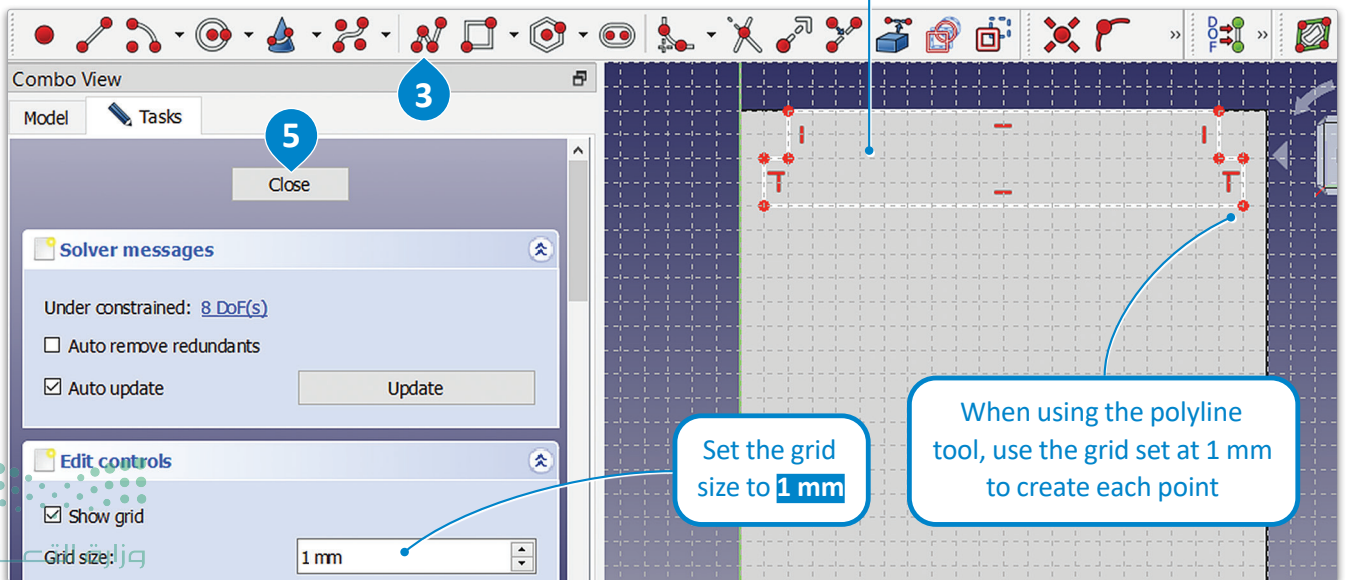
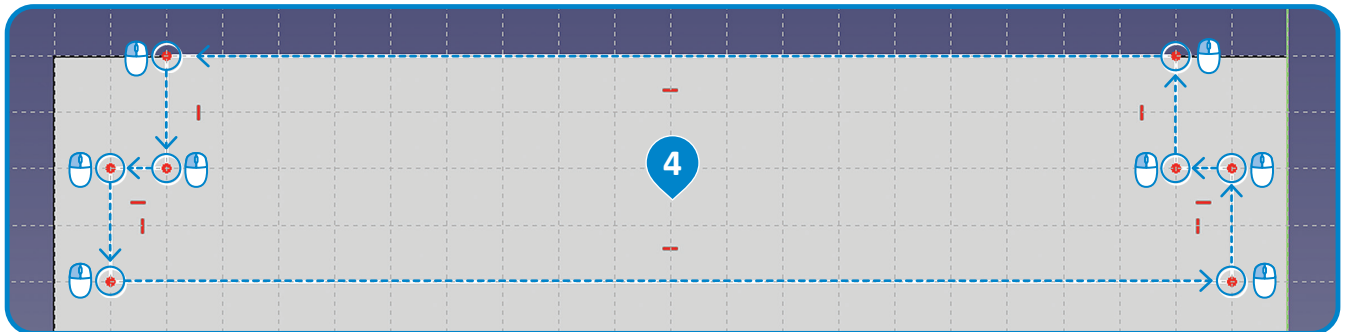


Figure 3.47: Creating a sketch on the top surface

To create a recess:

- > From the **toolbar**, select the **Pocket** tool. ①
- > In the **Pocket parameters** window, change the length to **147 mm** ② and click **OK**. ③

The shape created on the face of the Pillbox-Body

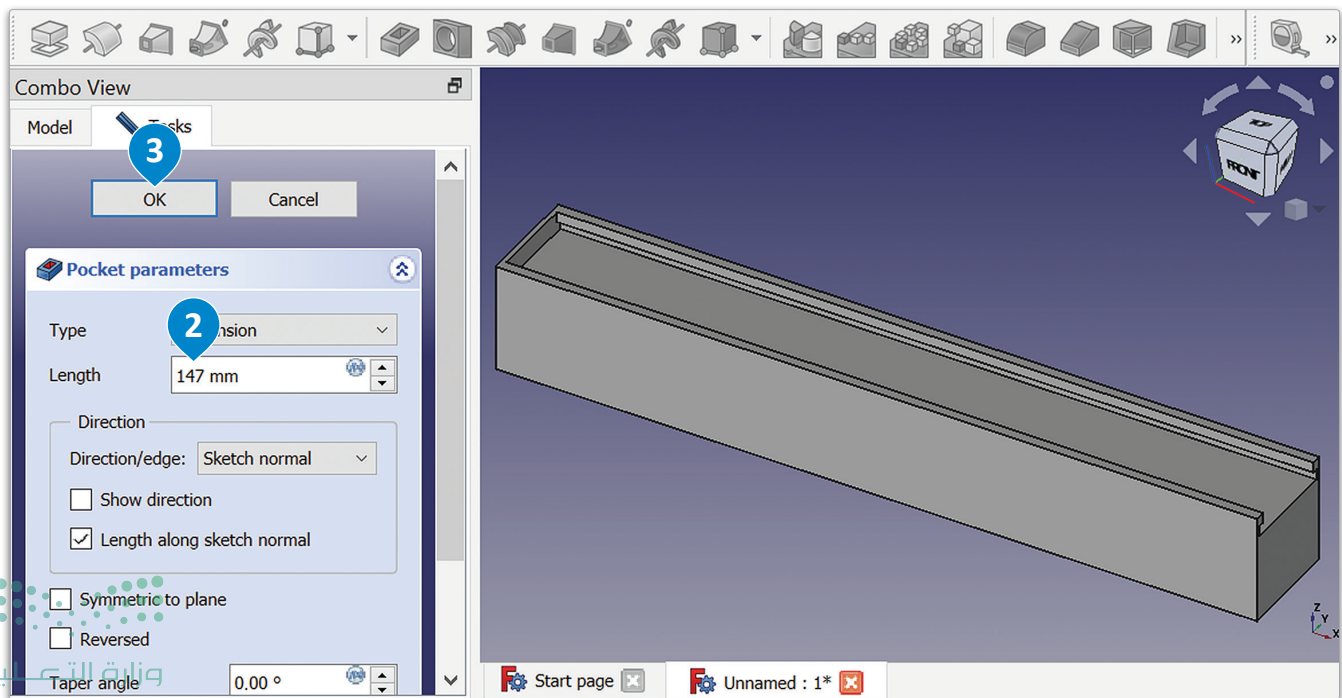
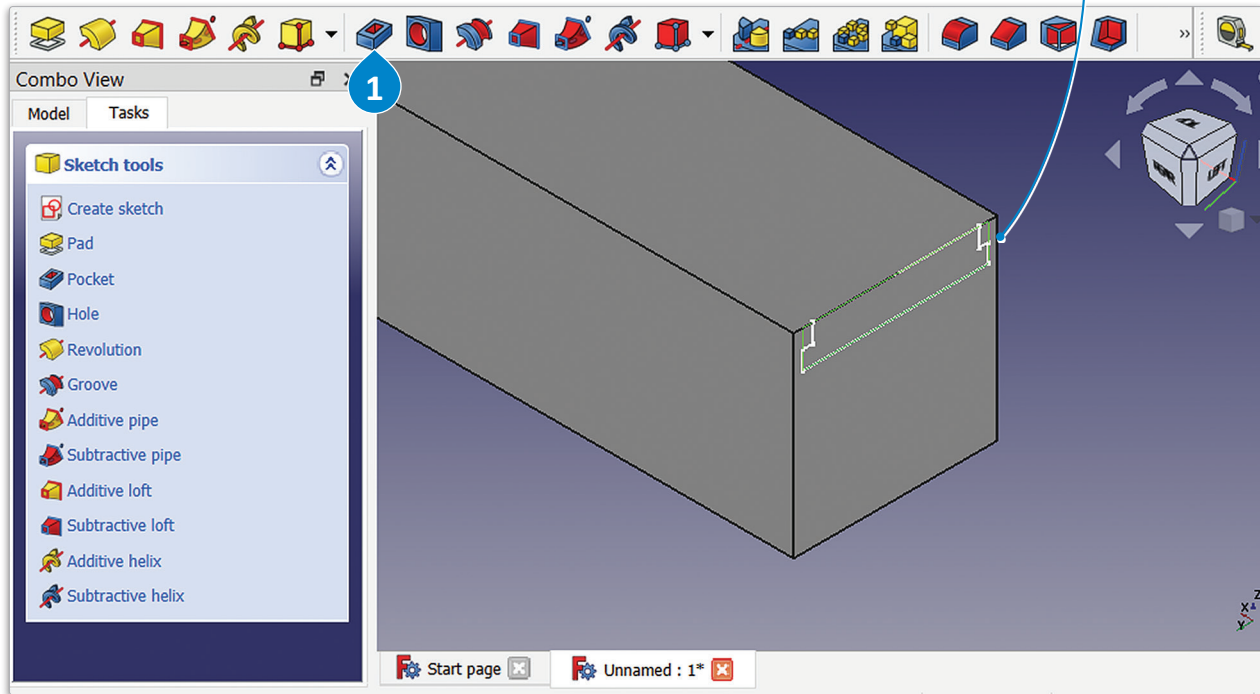
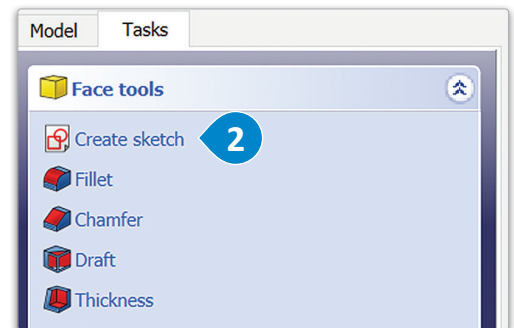
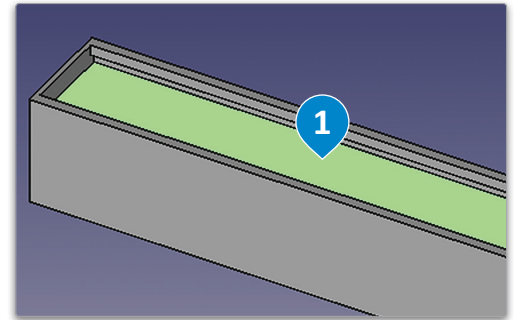


Figure 3.48: Creating a recess

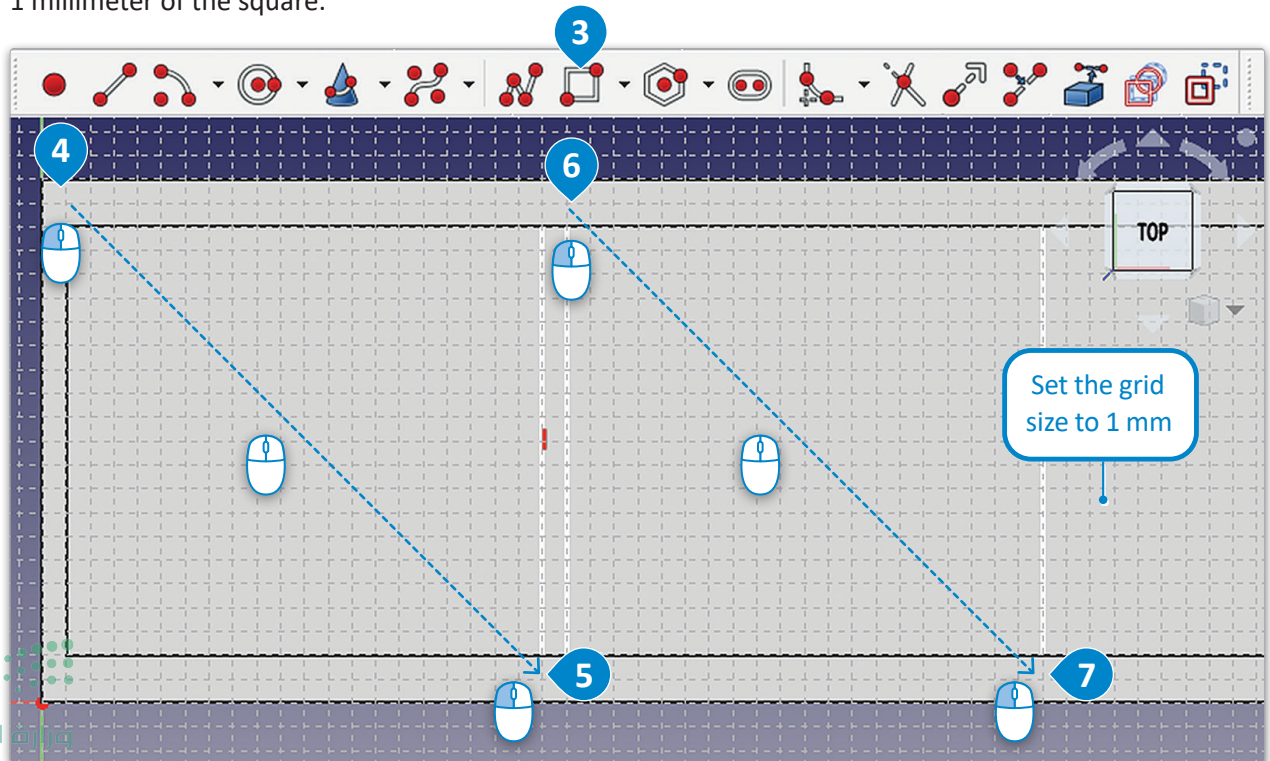
To create the seven boxes for the pills, you will need to use the rectangle tool and click on the long, recessed face of the Pillbox-Body, where you previously cut. You will need to make sure that there is a 1 mm separation between each of the boxes.

To create seven squares:

- > Click the **Pillbox-body** to select the upper surface. **1**
- > From the **Face tools**, select the **Create sketch** tool. **2**
- > Select the **Create rectangles** tool. **3**
- > Click on the sketch to set the first corner of the square. **4**
- > Move the cursor to set the opposite corner of the square and click again to create the square. **5**
- > Click on the sketch again to set the first corner of the second square. **6**
- > Move the cursor to set the opposite corner of the square and click again to create the square. **7**
- > Continue until you have seven squares. **8**
- > From the **Tasks** tab, click **Close**. **9**



When you draw the 20x20 square, you will notice that from the point you start and for 1 millimeter, the shape you will create cannot be seen because it is below the recess. The same applies to the last 1 millimeter of the square.



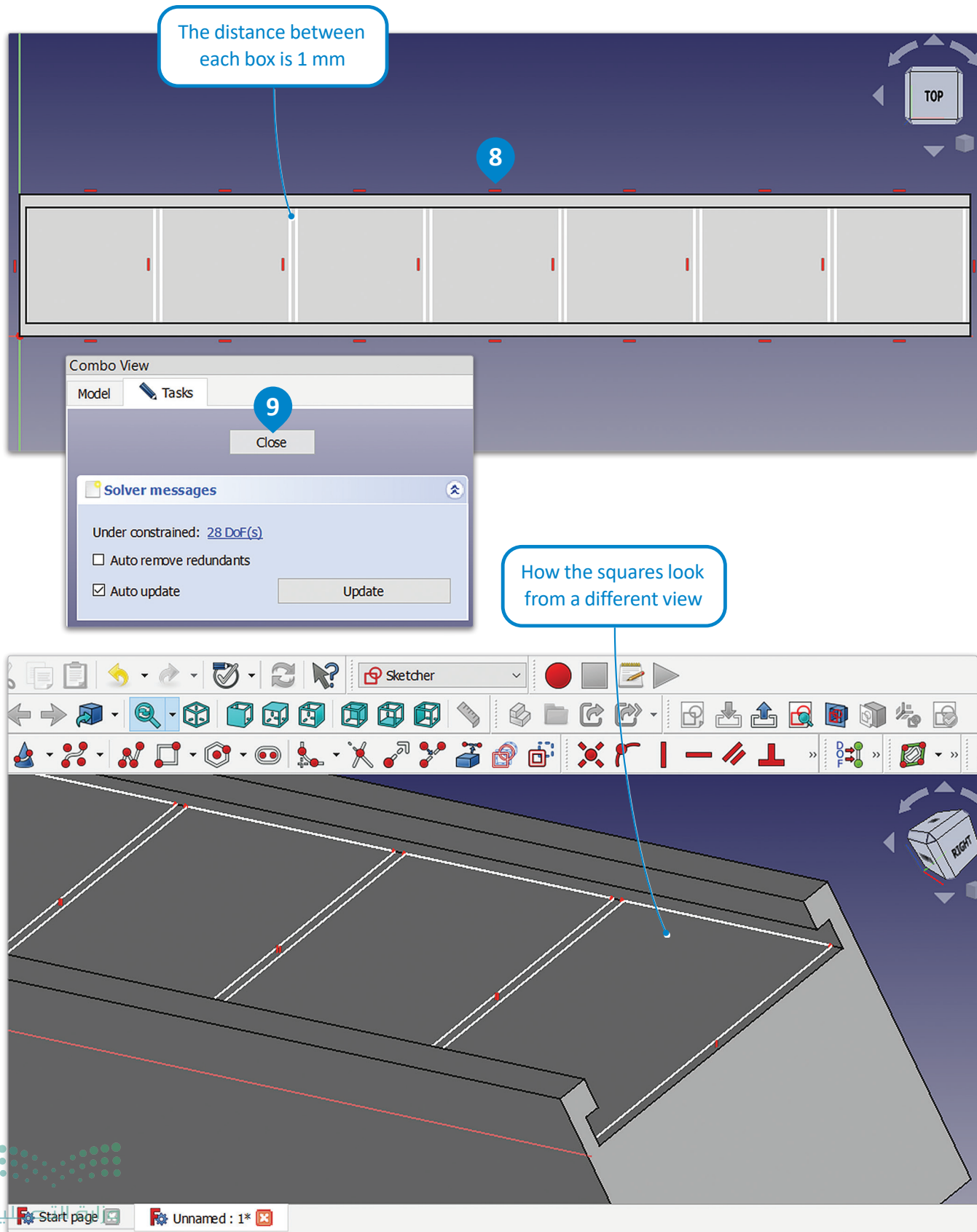


Figure 3.49: Creating seven squares

Now, let's use the Pocket tool to create the seven boxes.

To create a recess:

- > From the **toolbar**, select the **Pocket** tool. **1**
- > In the **Pocket parameters** window, change the length to **16 mm**, **2** and click **OK**. **3**

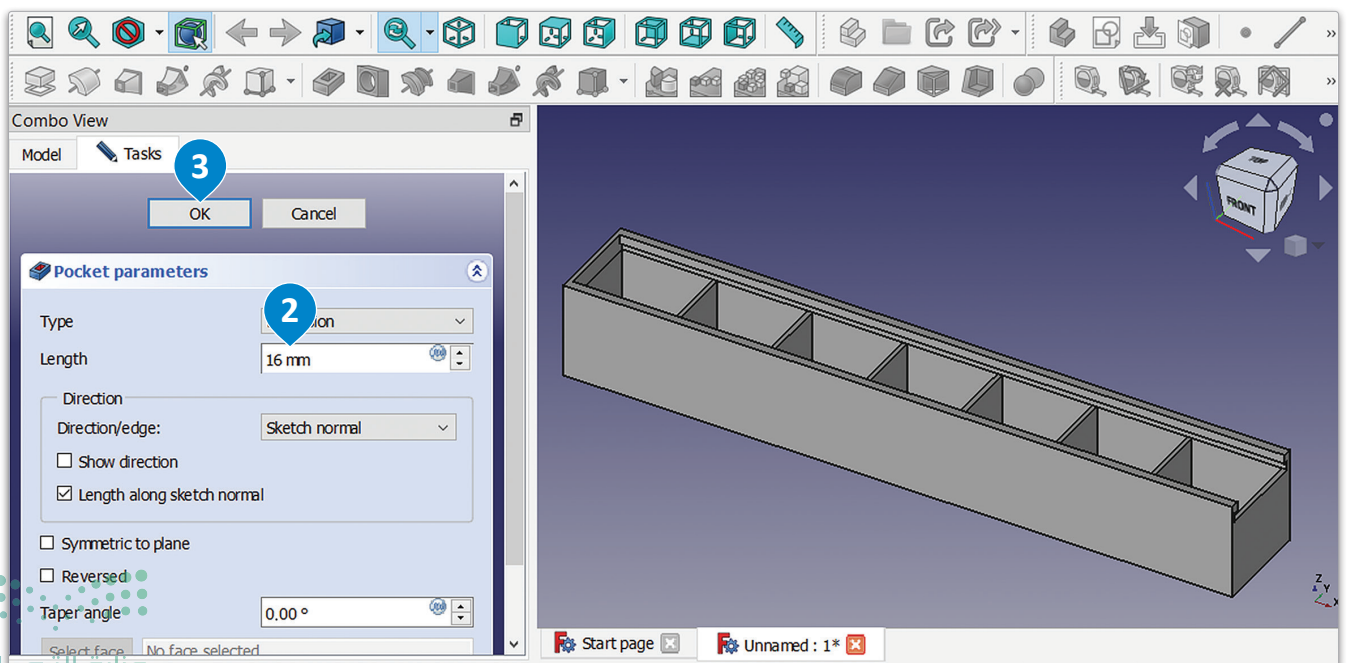
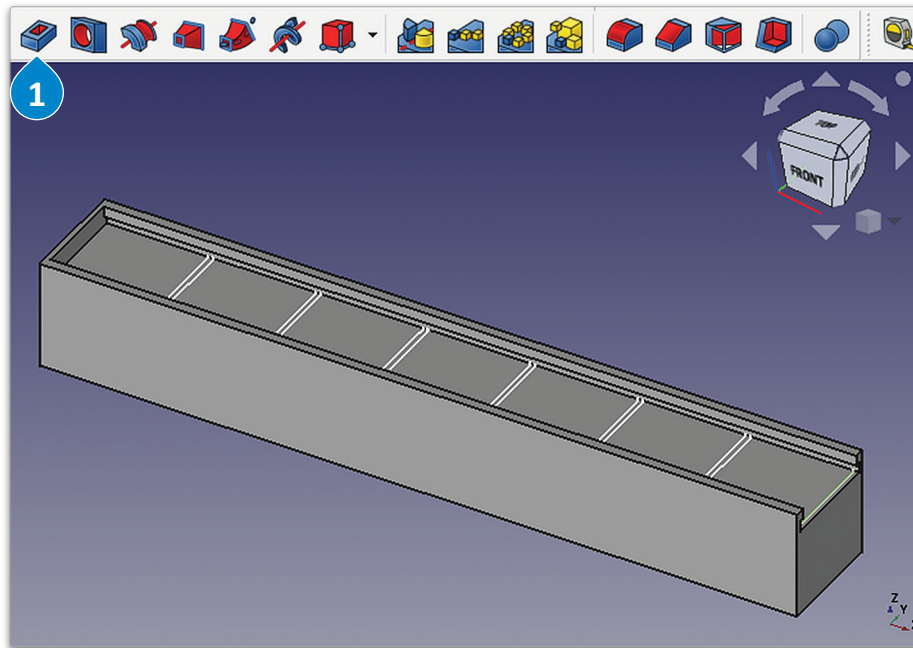


Figure 3.50: Creating the containers

Braille System

The Braille system is a tactile writing system used by visually impaired people. It uses raised dots to represent letters, numbers, and punctuation. You will use the braille system to label the days of the week on your pill box. You will create braille dots using the circle tool and extrude them with the pad tool. The braille dots will be placed on one of the long faces of the Pillbox-Body, in the center of each container box. A specific pattern of dots will represent each day of the week. For example, the first day of the week will be number one, the second day of the week the number two, and so on.

Tactile Writing

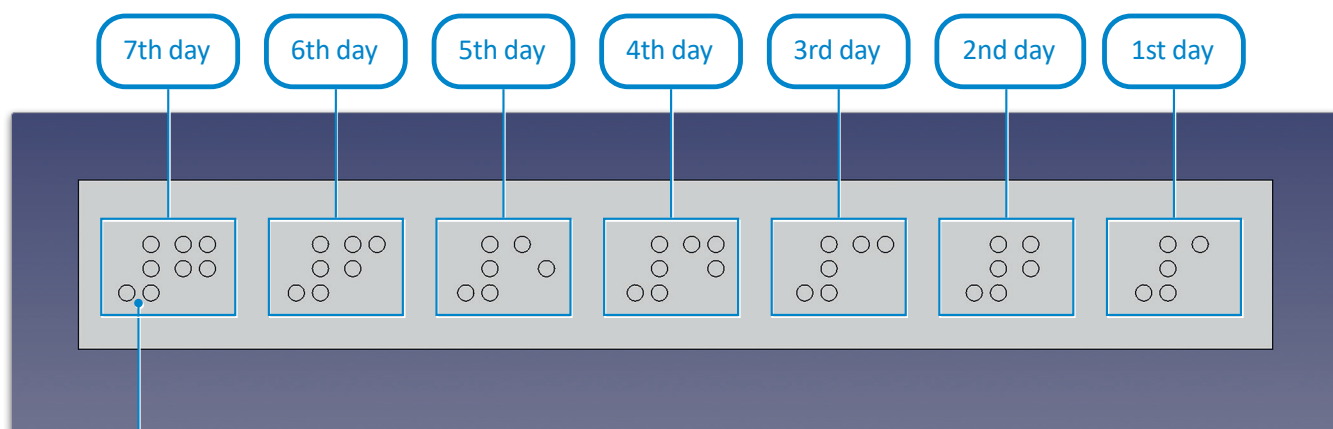
Tactile writing is a method of written communication that can be read by touch, typically by individuals who are visually impaired or blind.

Let's take a look at how the numbers are represented in the Braille system:

○ ●	● ○	● ○	● ●	● ●	● ○	● ●	● ●	● ○	○ ●	○ ●
○ ●	○ ○	● ○	○ ○	○ ●	○ ●	● ○	● ●	● ●	● ○	● ●
● ●	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○	○ ○
#	1	2	3	4	5	6	7	8	9	0

The Braille code can be used to represent the alphabet, numbers, punctuation marks, and other symbols.

Week days



In the Braille system, the sharp symbol, which is also called the number sign (#), is used to show that the next characters are numbers instead of letters.

To create the dots for the Braille system, start by clicking on the side of the Pillbox-Body. Then you will use the Create rectangles tool to create a rectangle. The rectangle will be used to center the dots for the Braille system.

To create a sketch on a surface:

- > Click the **Pillbox-Body** to select its surface. **1**
- > From the **Face tools**, select the **Create sketch** tool. **2**
- > From the **toolbar**, select the **Create rectangles** tool. **3**
- > Click on the sketch to set the first corner of the shape. **4**
- > Move the cursor to set the opposite corner of the shape, and click again to create the shape. **5**

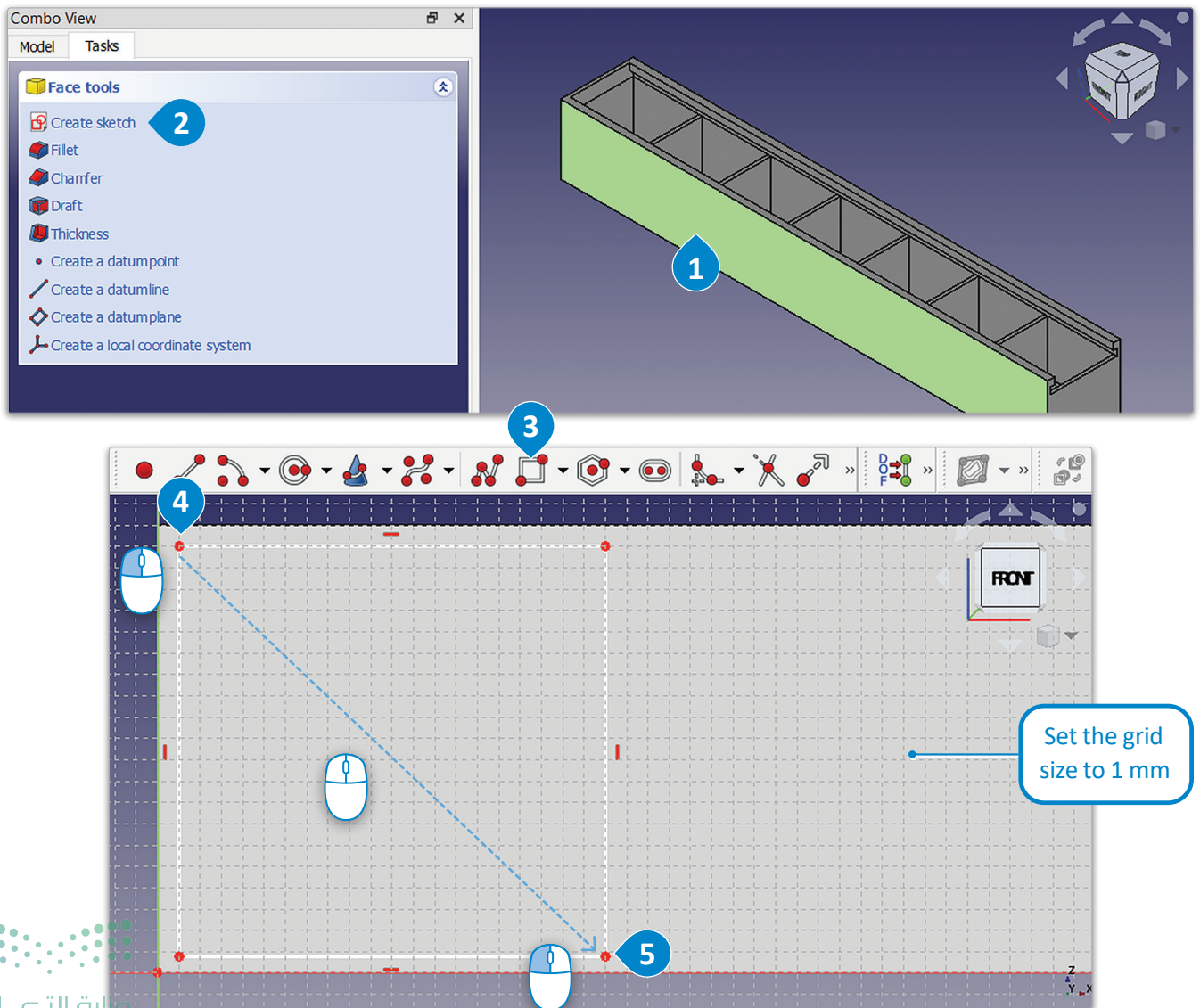


Figure 3.51: Creating a sketch on a surface

You will create the first number on your Pillbox-Body using the braille system. After creating the first circle, you will use the Copy tool to create the remaining circles.

To copy a sketch:

> From the **toolbar**, select the **Create circle** tool, **1**
click once to define the center of the circle and a second time to create a circle of radius 1 mm. **2**

> Click on the sketch, **3** hold the mouse button and move the cursor over the circle and release the mouse button to select it. **4**

> From the **toolbar**, select the **Copy** tool, **5** and click on the sketch to create a new circle. **6**

> Repeat until you have completed the Braille symbol as in the image. **7**

Clone:

The Clone tool creates a copy of an object or group of objects but keeps them linked to the original object.

Copy:

The Copy tool creates a new, independent copy of an object or group of objects.

Move:

The Move tool allows you to select one or more objects and move them to a new location in your workspace.

Clone

Copy

Move

If no shape is selected, the Copy tool cannot be used.

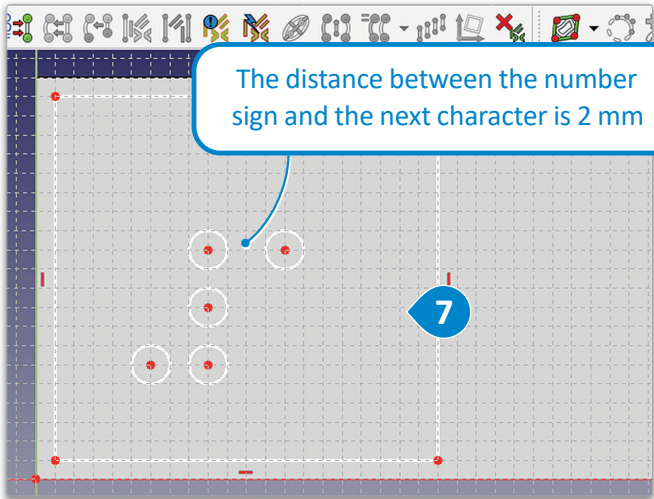
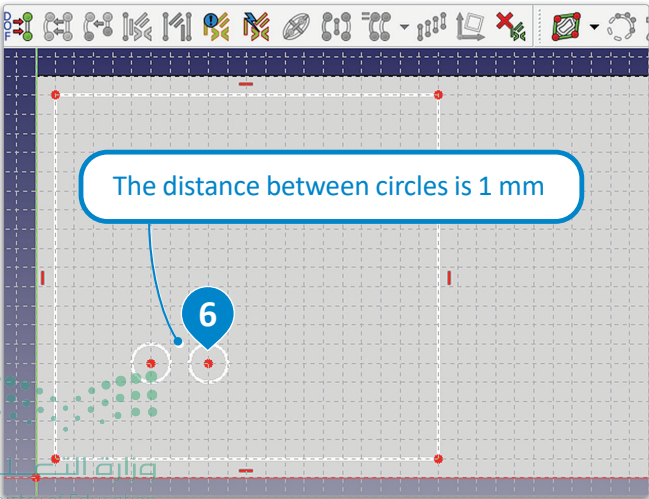
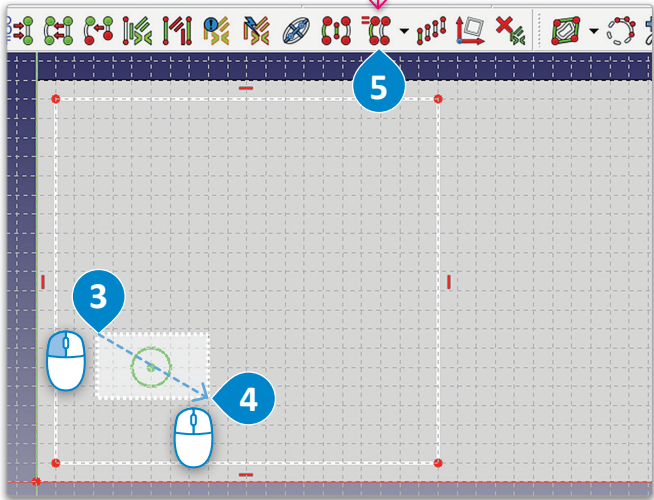
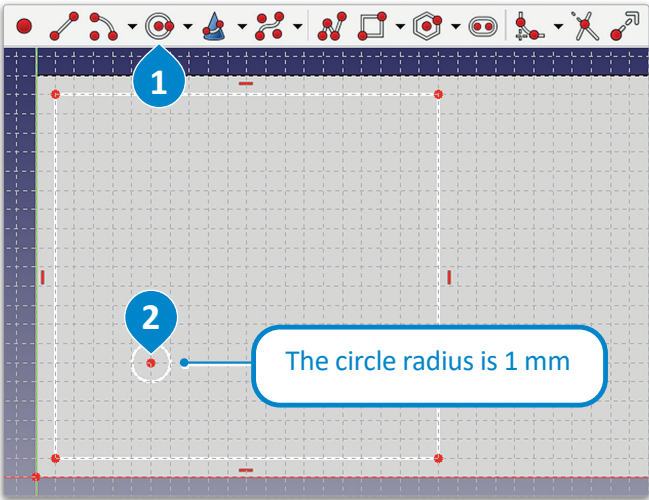
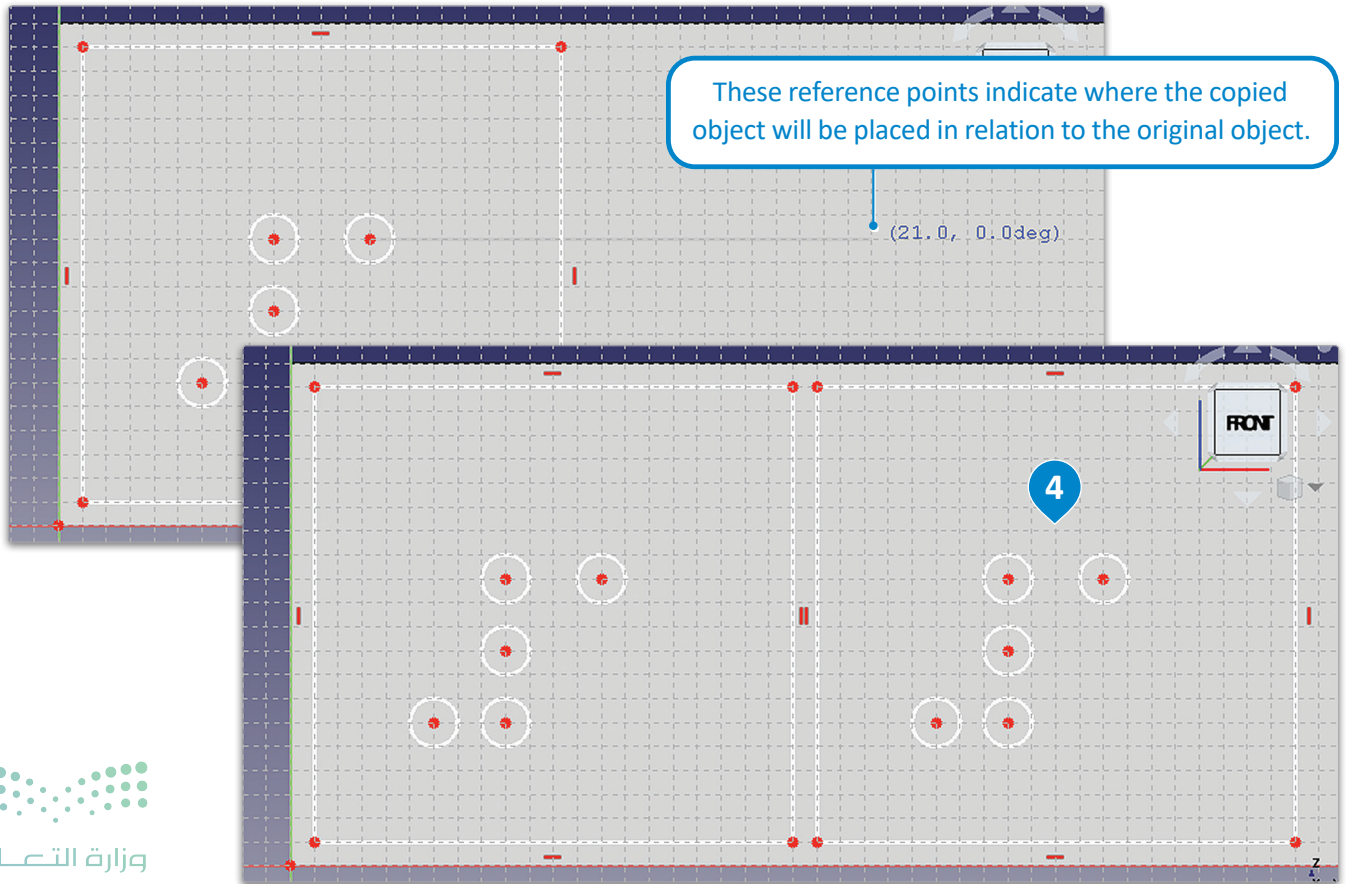
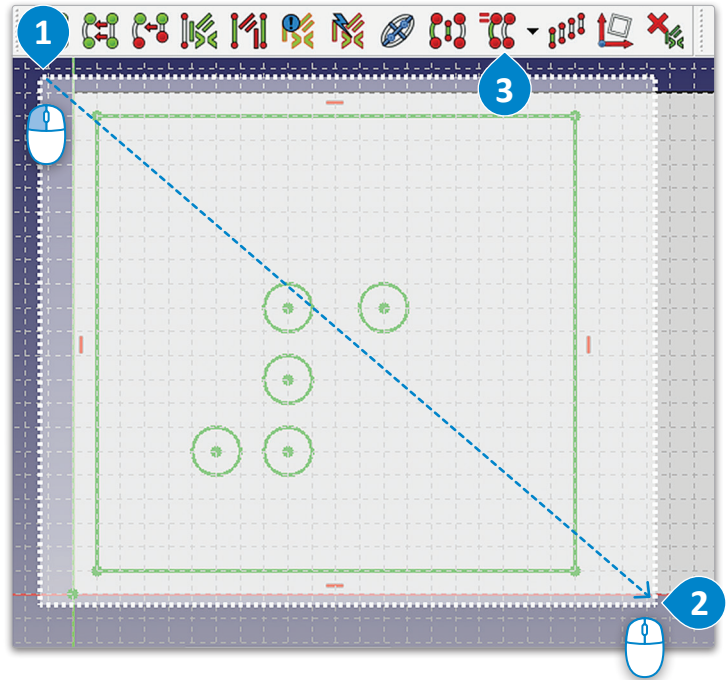


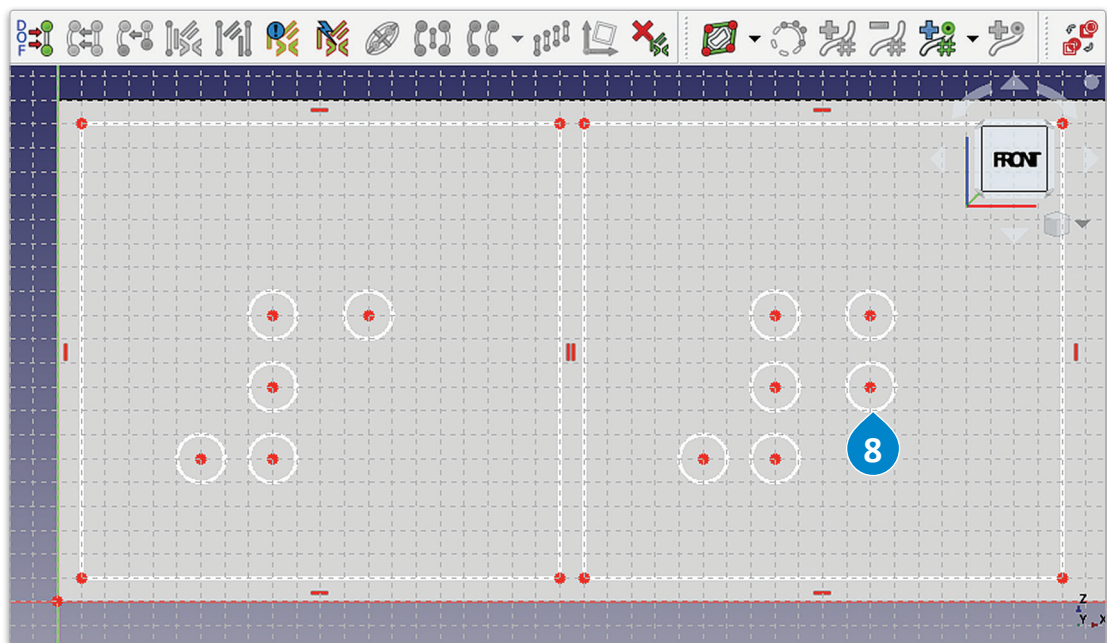
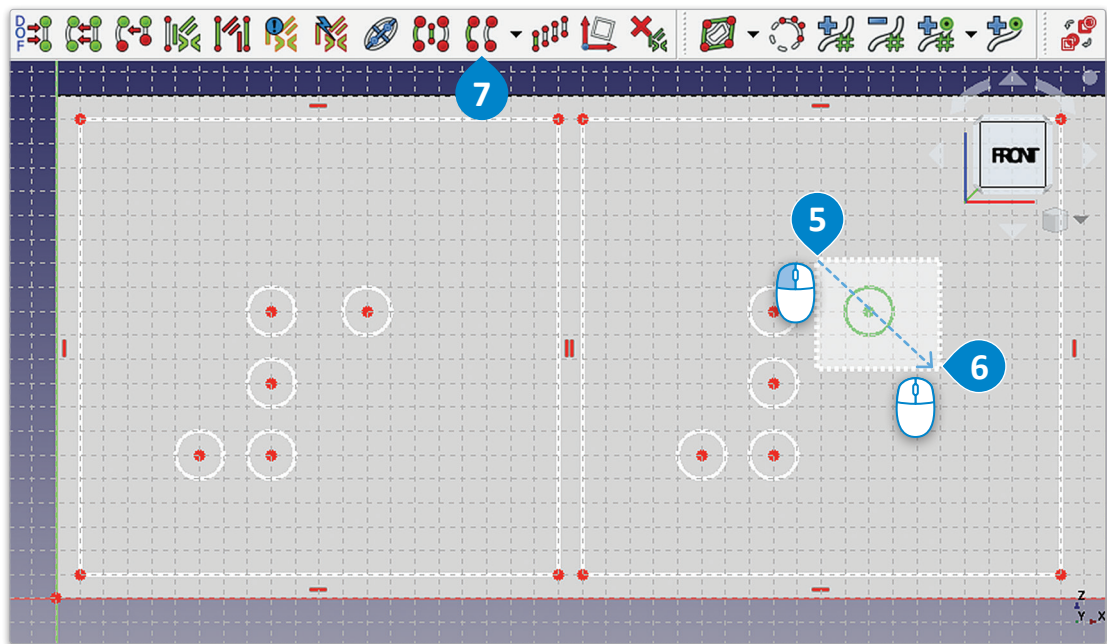
Figure 3.52: Copying a sketch

Next, you will copy all the sketches that you have created and duplicate them 21 mm to the right in order to create the second number on your Pillbox-Body. You will then edit the sketch to create the number 2.

To copy sketches:

- > Click on the sketch, **1** hold the mouse button and move the cursor over the sketches and release the mouse button to select it. **2**
- > From the **toolbar**, select the **Copy** tool, **3** and click on the sketch to create a new circle sketch 21 mm to the right. **4**
- > Click on the sketch, **5** hold the mouse button and move the cursor to over the circle and release the mouse button to select it. **6**
- > From the **toolbar**, select the **Copy** tool **7** and click on the sketch to create a new circle. **8**





Use the copy tool to create the five remaining numbers to complete the set of numeric symbols for the seven days of the week.

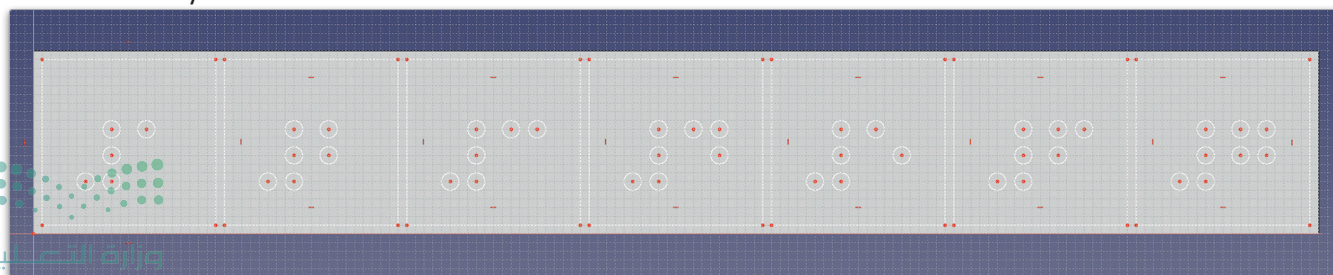


Figure 3.53: The days of the week represented using braille

To delete a sketch, you can select it and then press delete on your keyboard. For example, if you have copied and duplicated the sketches for the number two and want to create the number three, you can delete the green circle shown in figure 3.54.

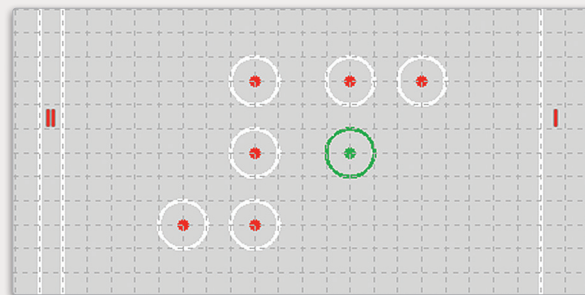
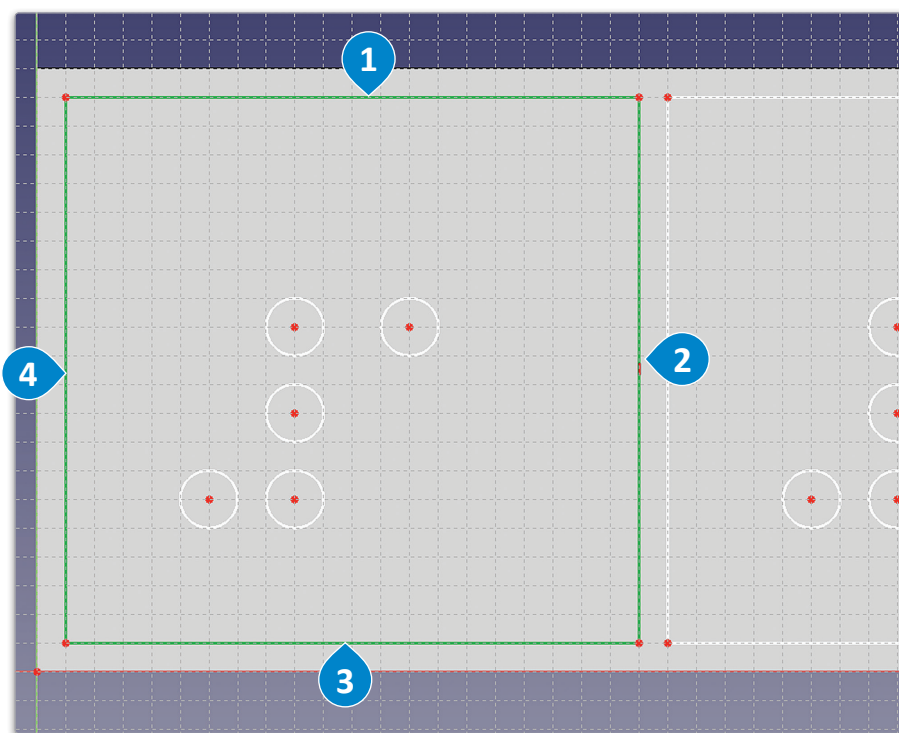


Figure 3.54: Delete a sketch

After you have finished creating the numbers, select the rectangles you used to place the dots and delete them.

To copy a sketch:

- > Hold the **Ctrl** key and select the top side, **1** the right side, **2** the right bottom side, **3** and the left side. **4**
- > Press **Delete** on your keyboard.



Your final sketch should look like the following image:

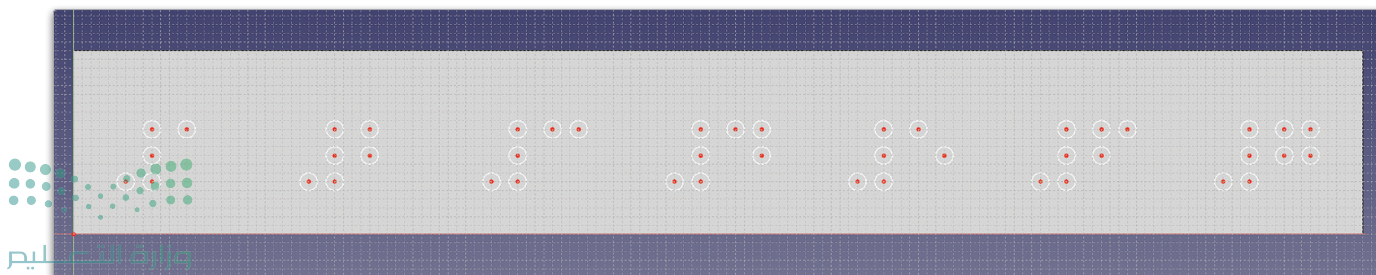


Figure 3.55: Final sketch

The Braille system uses raised dots or bumps that are felt with the fingertips to represent letters and other symbols. To create a similar sensation, you will use the Pad tool to raise the circles by 1 mm.

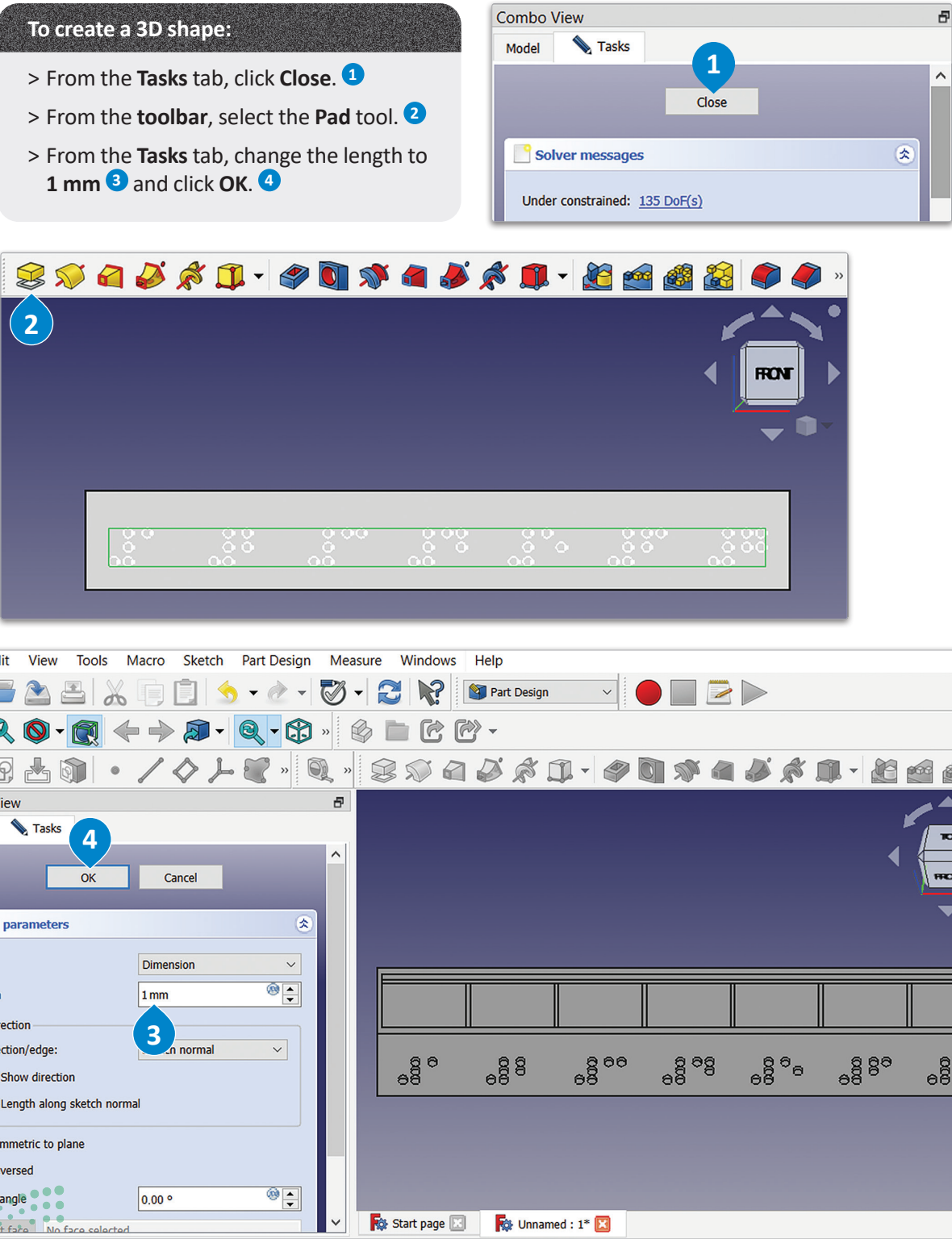
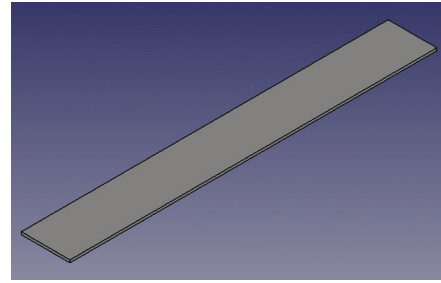


Figure 3.56: Creating a 3D shape

Designing the Pillbox-Cap

Now that you have completed the body of the pill box, you will create a pill box cap to seal and secure the medication. The pill box cap is an important component as it helps to prevent contamination and spills, and ensures that the medication remains secure and protected.



In 3D modeling, hiding a body can be helpful when creating another body because it allows you to see and work with the new body more efficiently. When multiple bodies are visible simultaneously, they can overlap and obstruct each other, making it difficult to see and manipulate the new body.

So let's make the Pillbox-Body invisible to be able to work with the Pillbox-Cap more efficiently.

To make the Pillbox-Body invisible:

- > From the **Combo View**, click the **Model** tab. ¹
- > From the **Menu bar**, click **View** ² and select **Toggle visibility**. ³

The entire object must be selected for this "Toggle Visibility" to be enabled in the menu.

Pillbox-Body is made invisible.

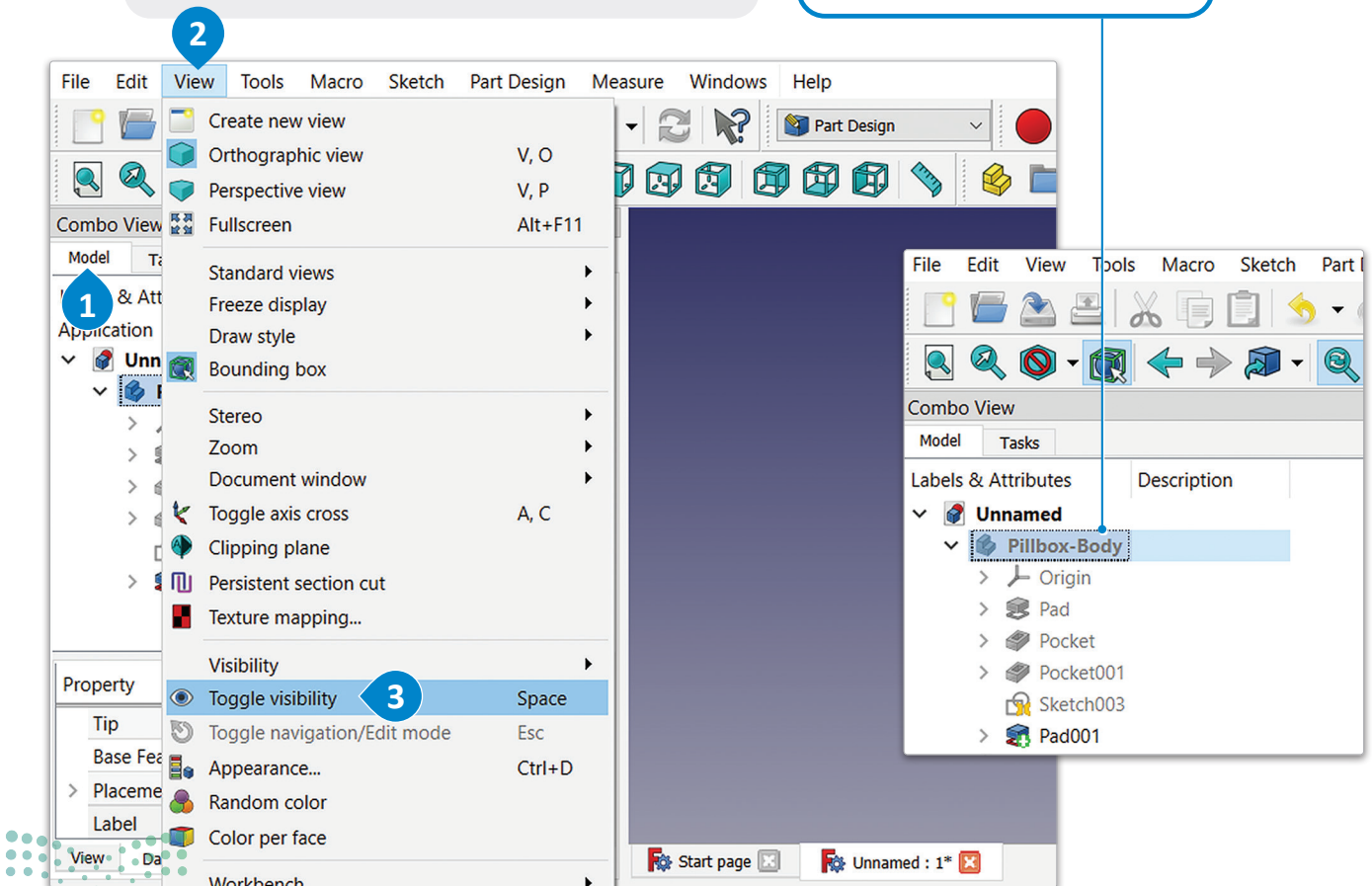


Figure 3.57: Making the Pillbox-Body invisible

Now you will create a new body for the cap and select the XY plane.

To create the Pillbox-Cap:

- > From the **toolbar**, click the **Create body** tool. **1**
- > From the **Model** tab, change the **Label** to **Pillbox-Cap**. **2**
- > From the **toolbar**, click the **Create sketch** tool. **3**
- > From the **Tasks** tab in the **Combo View**, click **XY_Plane**. **4**
- > From the **Tasks** tab in the **Combo View**, click **OK**. **5**

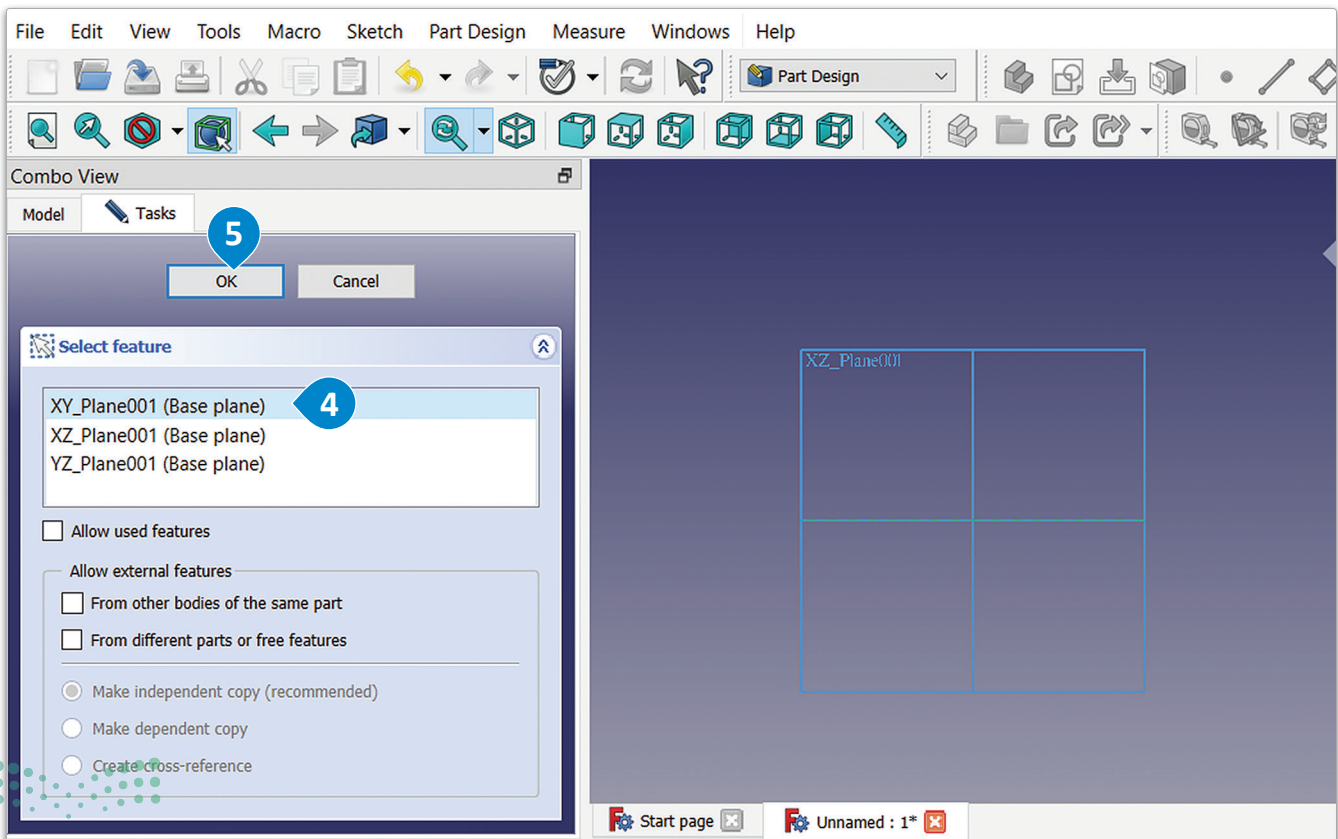
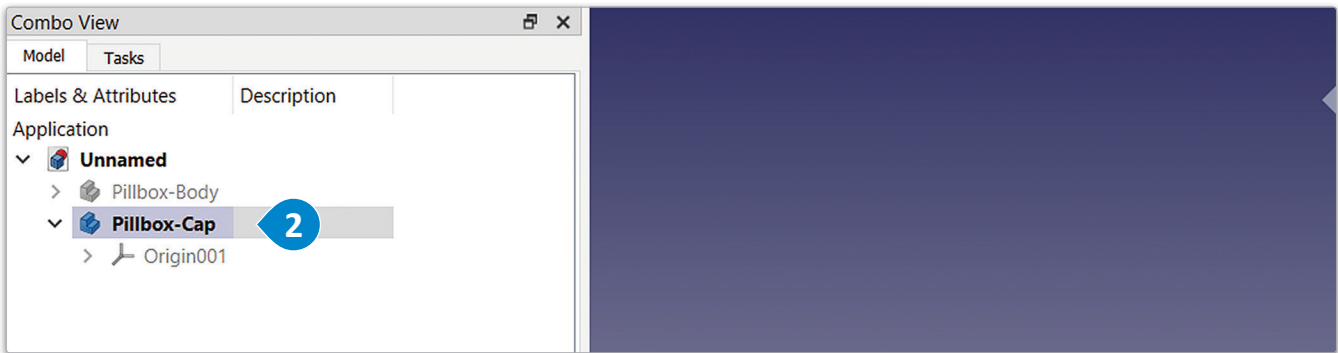
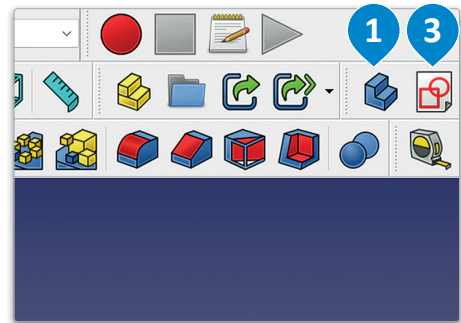


Figure 3.58: Creating the Pillbox-Cap

Now, use the Create rectangles tool to create a rectangle with length of 147 mm and a width of 19.5 mm.

To create a rectangle:

- > From the **toolbar**, select the **Create rectangles** tool. ①
- > Click on the sketch to set the first corner of the rectangle. ②
- > Move the cursor to set the opposite corner of the rectangle, and click again to create the rectangle. ③

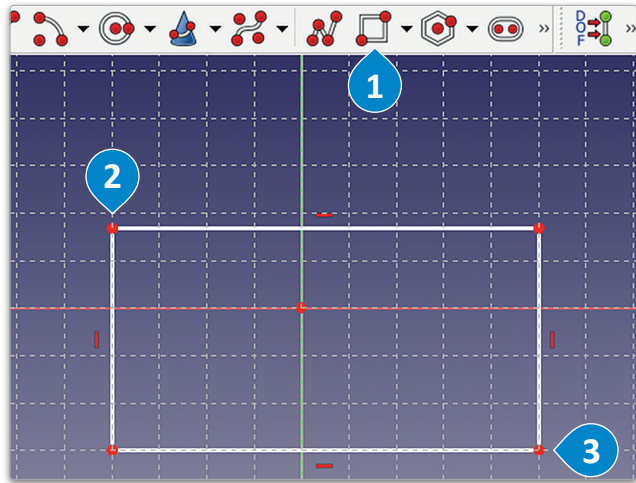
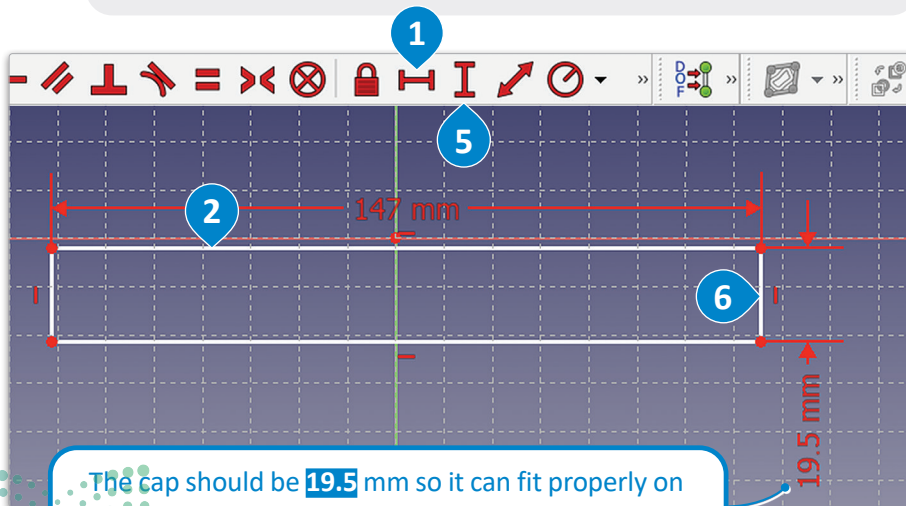
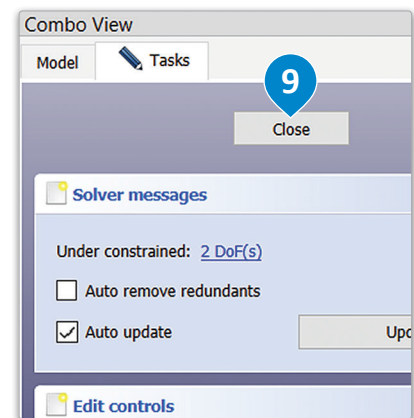
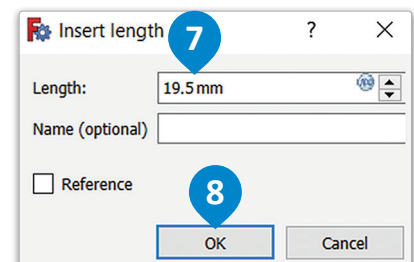
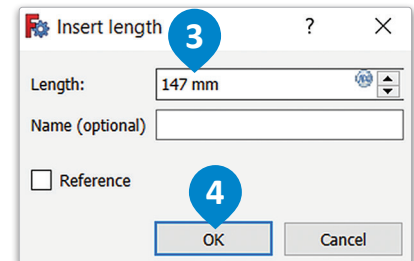


Figure 3.59: Create a rectangle

Use constraints to set the rectangle length to 147 mm and the width to 19.5 mm.

To constrain horizontal and vertical distance:

- > From the **Constraints toolbar**, select the **Constrain horizontal distance** tool. ①
- > Click on the upper edge of the rectangle. ②
- > Set the **Length** to **147 mm** ③ and click OK. ④
- > From the **Constraints toolbar**, select the **Constrain vertical distance** tool. ⑤
- > Click on the right edge of the rectangle. ⑥
- > Set the **Length** to **19.5 mm** ⑦ and click OK. ⑧
- > From the **Tasks** tab, click **Close**. ⑨



The cap should be **19.5 mm** so it can fit properly on the pill box body and not leave any gaps at the edges.

Figure 3.60: Constraining the horizontal and vertical distance

Finally, use the Pad tool to extrude the rectangle into a 3D shape.

To create a 3D shape:

- > From the **toolbar**, click the **pad** tool. **1**
- > From the **Tasks** tab, change the length to **1 mm** **2** and click **OK**. **3**

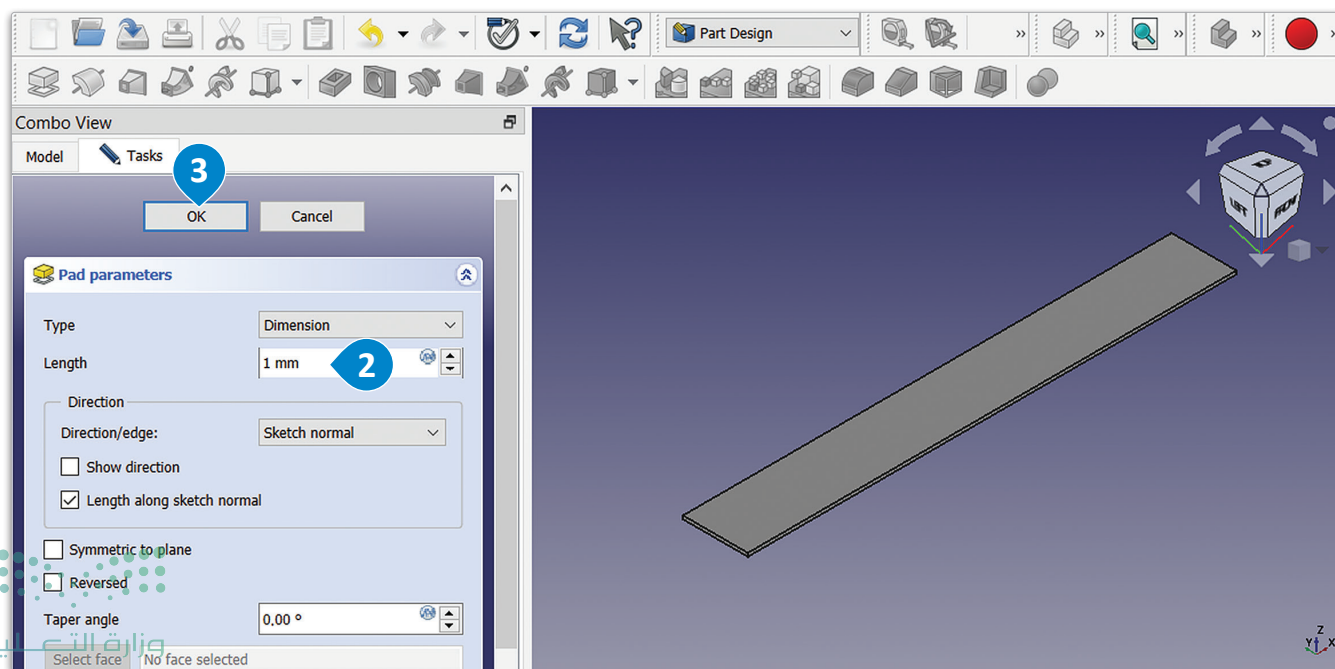
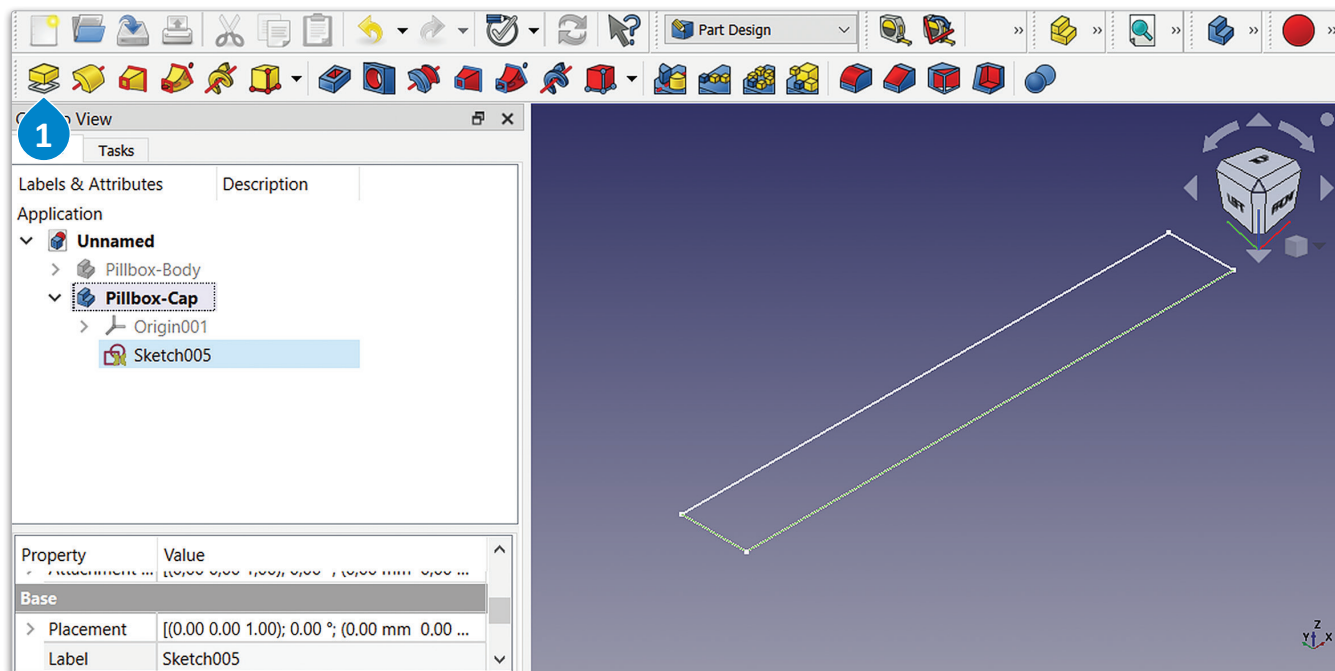


Figure 3.61: Creating the Pillbox-Cap

Now that you have completed the pill box design phase, it's time to prepare the file for printing.

Once you have the OBJ files, you will use Ultimaker Cura to create the GCODE file that the 3D printer needs to print the pill box.

To create the file for printing:

- > In **Ultimate Cura** open the .obj files. **1**
- > Click on the **Slice** button. **2**
- > From the **Menu bar**, click **File** **3** and select **Export....** **4**
- > Click on the **Documents** folder. **5**
- > Type a name. **6**
- > In the **Save as type**: drop down menu, select **G-code File (*.gcode)**, **7** and click **Save**. **8**

Export the two bodies as obj files so that you can prepare them for 3D printer.

Pillbox_Body.obj
Pillbox_Cap.obj

Choosing a file format compatible with your 3D printer and the software you are using is essential.

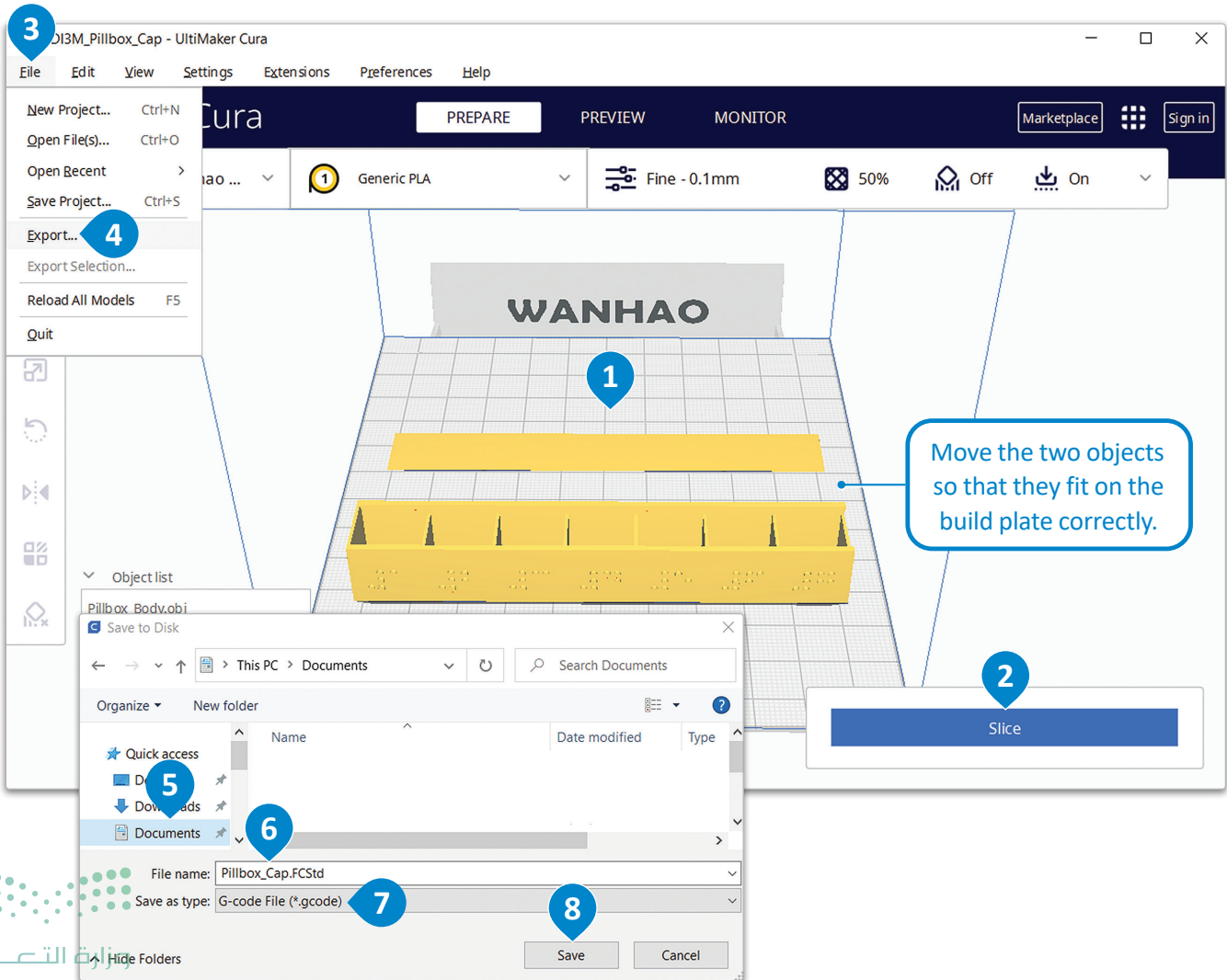


Figure 3.62: Exporting the two models

Exercises

1

Read the sentences and tick ✓ True or False.	True	False
1. The Polyline tool can be used to create a series of connected line segments that form a closed shape.	☐	☐
2. The grid size is not important for creating precise and accurate designs.	☐	☐
3. The Clone tool creates a new, independent copy of an object or group of objects.	☐	☐
4. When using the Copy tool to duplicate an object, reference points are automatically created to indicate where the copied object will be placed in relation to the original object.	☐	☐
5. The Move tool in FreeCAD allows you to select one or more objects and move them to a new location in your workspace.	☐	☐
6. Making a body invisible can be helpful when creating another body, as it allows you to see and work with the new body more efficiently.	☐	☐
7. When using the Pocket tool to cut out a shape, it is important to set the depth of the pocket to match the thickness of the material being used.	☐	☐
8. When using the Polyline tool to create a series of connected line segments that form a closed shape, it is not possible to edit or modify the shape once it is created.	☐	☐

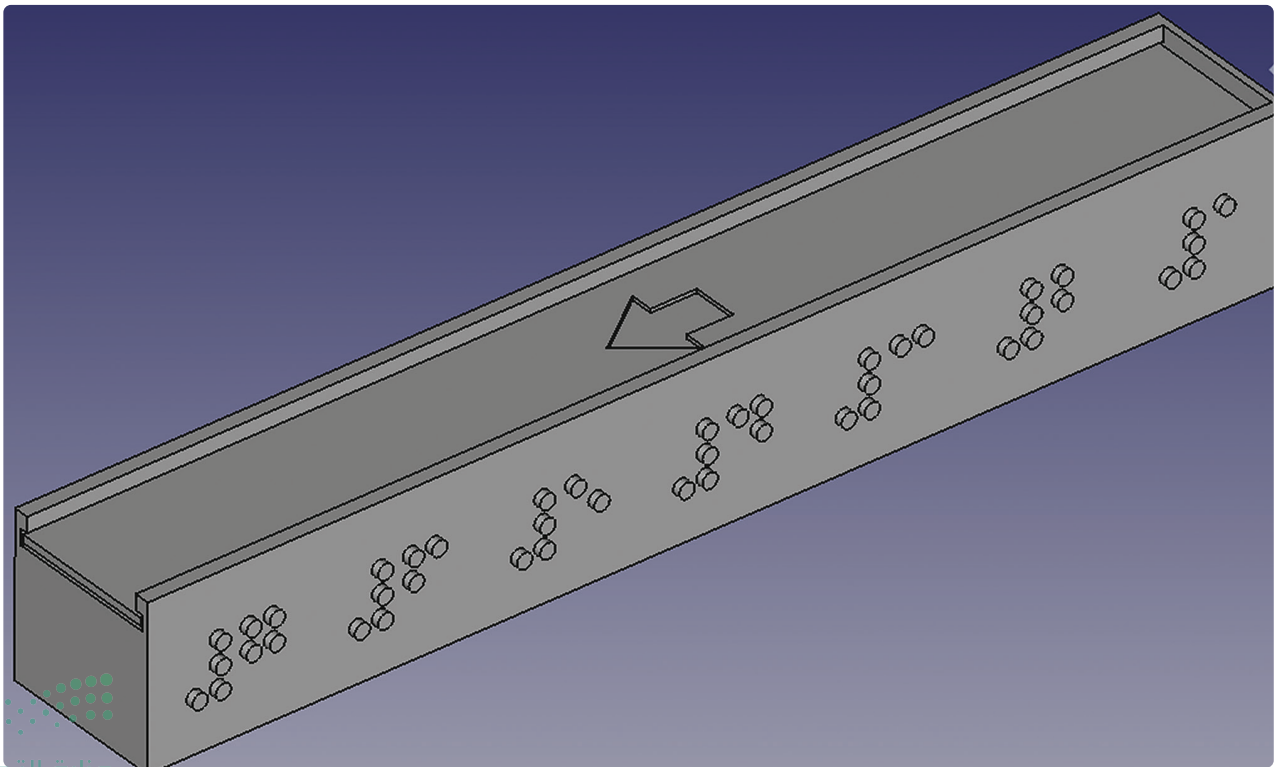
2 Explain why it is important to consider the size of the pill box when designing it for 3D printing?



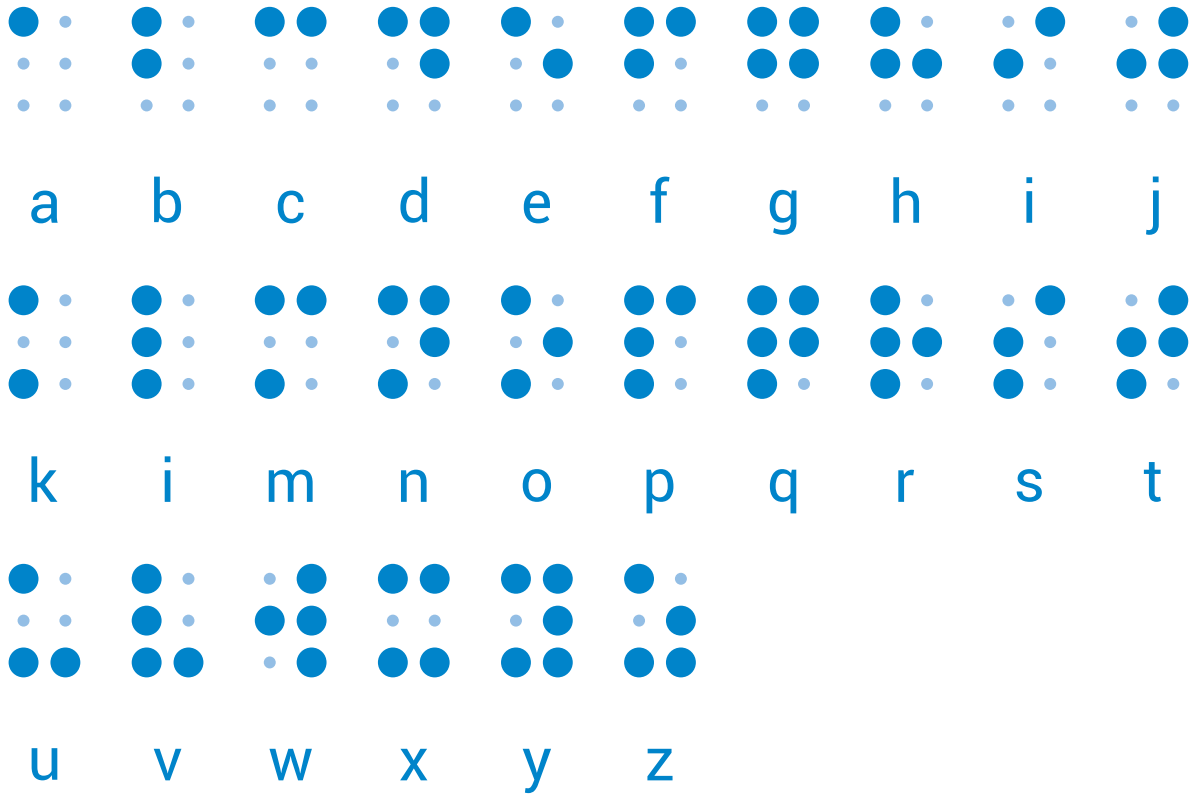
- 3 In what ways can working with a smaller grid size help to develop your design skills and attention to detail? Search on the Internet to find out how might these skills be useful in other areas of engineering or design work.

- 4 The pill box design includes a recess for a cap to secure stored pills inside the containers. Improve this design to make it more user-friendly for individuals with limited dexterity or mobility.

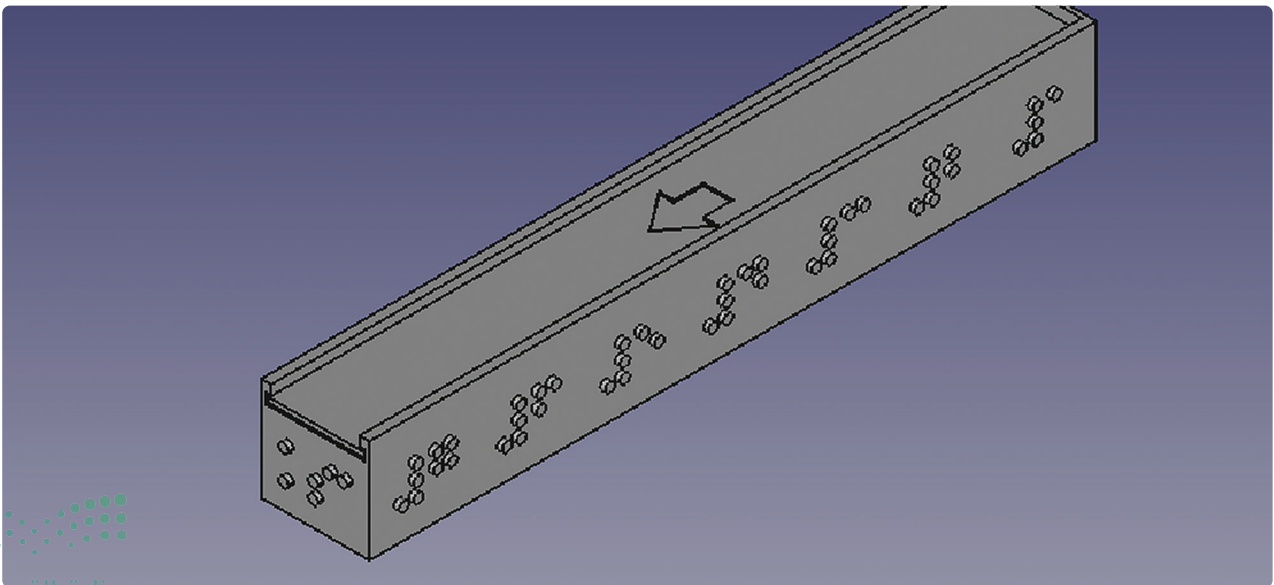
Use the image below to create an arrow shape in the Pillbox-Cap body that will allow users to slide the cap more easily.



5 Design the letters KSA in Braille using the Braille alphabet below.

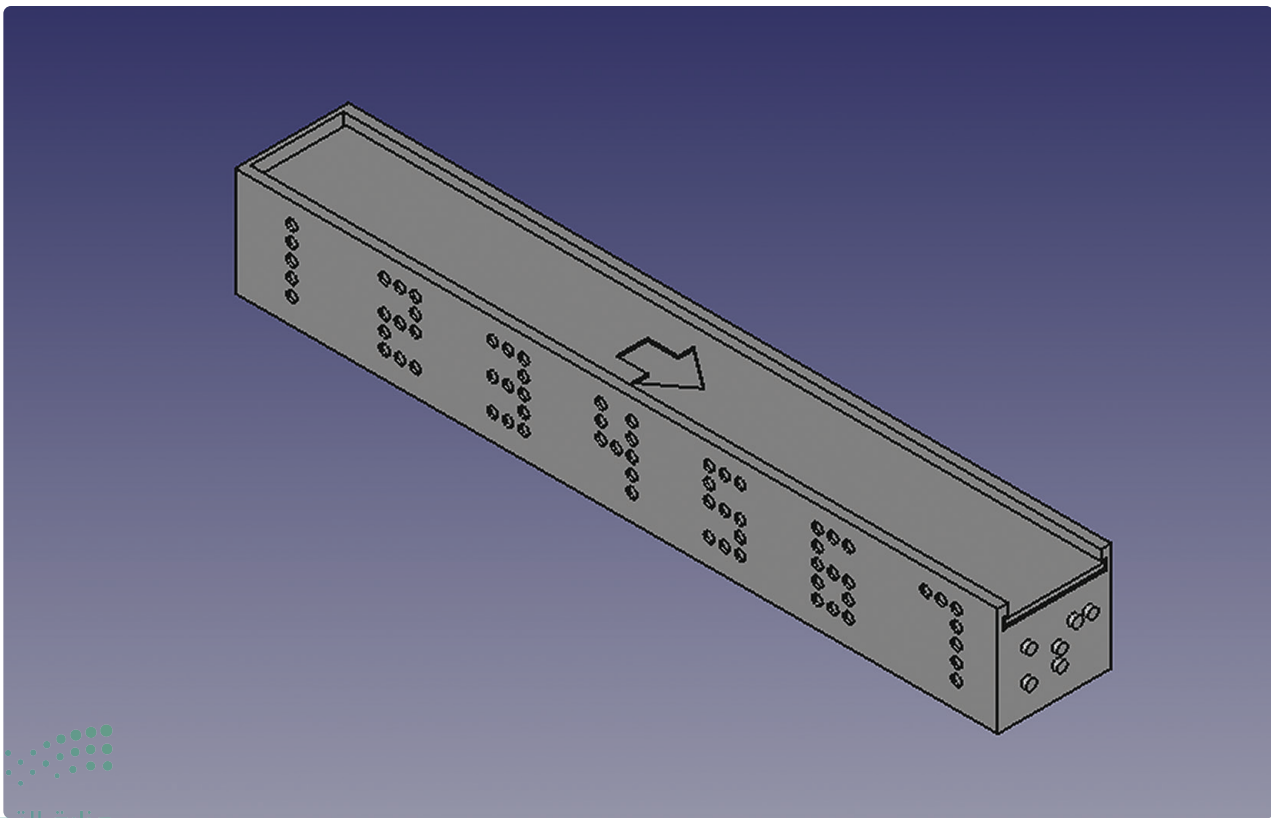


Use the following image to help you understand how to design the letters.



- 6 The pill box design incorporates the use of braille dots to label the days of the week. How might you modify this design to make it accessible for individuals who do not read braille or do not have visual impairments?

Use the following image to create labels using digital numbers or create your own labeling. Note: You will use the Pocket tool for the labels, with length 0.50 mm.





Testing and Refining a 3D Printed Product

Creating prototypes with a 3D printer is a process where design faults and mistakes are common when transitioning from CAD designs to physical form. Identifying and fixing issues early on can save time and avoid cost before moving on to manufacturing with more expensive materials. Rapid prototyping enables us to create a design, test its functionality, document any issues, improve the design, and print the next version of the prototype, without wasting time and expensive materials.

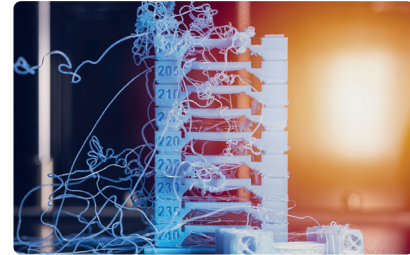


Figure 3.63: Example of a failed 3D printed part

Testing

Pre-Testing

Before conducting any tests, it is important to establish a testing plan. The testing plan should outline the tests, criteria, and other relevant information about the testing process. The plan should also specify the resources needed for testing, such as materials, equipment, and personnel. The process would be the following for testing a 3D printed prosthetic limb, as the one shown in figure 3.63:



- 1. Define testing objectives:** The first step is to define the objectives of the pre-testing process. This may include evaluating the design, functionality, and user experience of the prosthetic limb and identifying any defects or technical issues that need to be addressed.
- 2. Establish testing criteria:** Next, establish specific criteria that will be used to evaluate the prosthetic limb. This may include the aesthetics, ergonomics, and functionality of the limb, as well as its durability and ease of maintenance.
- 3. Determine testing processes:** Identify the specific tests that will be conducted to evaluate the prosthetic limb. This may involve having testers wear the prosthetic limb and perform various tasks related to daily living, such as picking up objects, typing on a keyboard, or climbing stairs.
- 4. Identify testing resources:** Determine the materials, tools, and equipment needed for the testing process. This may include 3D printers, testing software, and a team of experienced testers.
- 5. Establish a testing timeline:** Establish a timeline for the pre-testing process, including time for testing, analysis of results, and implementation of any necessary changes or fixes.
- 6. Develop a testing report:** After completing the pre-testing process, develop a testing report that outlines the results of the testing, identifies any issues or areas for improvement, and recommends changes or fixes that should be made before the prosthetic limb is released to the market.

Virtual Testing

It is common practice for virtual testing to be performed first, using computer-aided simulations. These simulations can help identify potential issues with the design and performance of the product before it is physically tested. For example, figure 3.64 shows a simulation of a knee replacement component inserted into a person's bone structure. As discussed earlier, testing may include simulations of stress and strain, fluid dynamics, or thermal analysis, among others. The process of virtual testing for a prosthetic limb would involve the following:

- 1. Develop virtual environments:** Create virtual environments that simulate real-world scenarios in which the prosthetic limb would be used. This may include virtual simulations of everyday tasks such as walking, typing, or driving.
- 2. Conduct testing:** Have testers use the 3D printed prosthetic limb in the virtual environments and perform specific tasks related to the testing scenarios. Collect feedback from testers on their experience, including any issues or bugs they encountered.
- 3. Analyze results:** Analyze the testing results to identify any patterns or issues that emerged during testing.



Figure 3.64: 3D representation of a knee replacement



Figure 3.65: Testing a prosthetic hand

Physical Testing

This stage involves physically testing the 3D printed prototype to evaluate its performance and identify any issues that need to be addressed. Various physical tests, such as strength and durability tests, dimensional accuracy tests, and environmental tests, may be performed. The process for physical testing for the prosthetic limb, as shown in figure 3.65 would be the following:

- 1. Develop physical testing environments:** Create physical testing environments that simulate realworld scenarios in which the prosthetic limb would be used. This may involve creating obstacles or challenges that the prosthetic limb must navigate, such as stairs or uneven terrain.
- 2. Conduct testing:** Have testers wear the 3D printed prosthetic limb and use it in the physical testing environments to perform specific tasks related to the testing scenarios. Collect feedback from testers on their experience, including any issues or discomfort they encountered.
- 3. Analyze results:** Analyze the testing results to identify any patterns or issues that emerged during testing. This may involve using specialized testing equipment to measure the prosthetic limb's performance and fit.

Refining a 3D Printed Product

The refinement stage of developing a 3D printed product is a critical step in the process. During this stage, the product design is reviewed and improved based on feedback from testing and evaluation. The stages of refining a printed product are the following:

Polishing 3D Printed Parts

Polishing 3D printed parts is an important step during the refinement phase, as it can greatly improve the surface finish and aesthetics of the final product. Depending on the material and the desired finish, various techniques can be used, such as sanding, grinding, or chemical smoothing. Polishing is particularly important with SLM printing technologies, as the surface finish of the final product is often rough and porous due to the nature of the process.

Analyzing testing results

The first step in the refinement process for a 3D printed prosthetic limb is to analyze the testing results. This involves reviewing data collected during testing and identifying any flaws or issues that must be addressed. For example, if the prosthetic limb did not fit comfortably on the user, the team would need to identify the specific parts of the prosthetic limb that need to be redesigned or modified. This process is shown on figure 3.66.

Identifying design modifications

Based on the analysis of the testing results, the team will identify required design modifications that need to be made to the 3D model. These modifications can include changes to the prosthetic limb's dimensions, features, materials, or other design elements. For example, if the prosthetic limb is too heavy, the team may modify the design to reduce the weight while maintaining the required strength.

Iterative design changes

Once the design modifications have been identified, the 3D model is updated with the changes, and a new prosthetic limb prototype is printed. The team will then repeat the testing process with the new prototype to verify that the changes have addressed the identified issues. This iterative process may be repeated several times until the final prosthetic limb design is achieved.

Review and approval

The prosthetic limb design is reviewed throughout the refinement stage by stakeholders, including designers, engineers, and clients. Feedback is collected, and changes are made to ensure the final prosthetic limb meets all requirements. The team will continue to review and refine the design until all stakeholders are satisfied and approve the final prosthetic limb.

Documentation

Finally, the development team will document all design changes and testing results to ensure that the final prosthetic limb meets all specifications and can be reproduced in the future. This documentation can include 3D models, test data, and any other relevant information about the prosthetic limb design and development process. The documentation is essential to the refinement stage and ensures that the final prosthetic limb meets the original requirements and design specifications.



Figure 3.66: Prototype testing of a prosthetic arm

Testing Tools for 3D Printed Products

FEA (Finite Element Analysis) software

FEA software simulates the behavior of 3D printed products under different loads and stresses. This software can identify potential issues and areas for improvement in the product design before physical testing is performed.

Digital calipers

Digital calipers are an essential tool for measuring the dimensions of 3D printed products. They can be used to ensure that the printed product's measurements match the 3D model and meet the required specifications.

Tensile testing machine

A tensile testing machine can test the strength and durability of 3D printed products. This machine can apply force to the product until it breaks, allowing the team to identify weak points in the design that must be addressed.

X-ray machine

An X-ray machine can examine the internal structure of 3D printed products. This can help identify defects or imperfections in the product that may not be visible on the outside.

Surface roughness tester

A surface roughness tester can measure the surface finish of 3D printed products. This can help ensure that the product has a smooth surface and meets the required specifications.

Scanning electron microscope

A scanning electron microscope can examine the surface of 3D printed products at a microscopic level. This can help to identify any defects or imperfections that may be too small to see with the naked eye.

Spectrophotometer

A spectrophotometer is an instrument that can measure the color of 3D printed products. This can be especially useful for products that require specific color matching, such as consumer products or parts for machinery.

Dye penetrant testing

Dye penetrant testing is a non-destructive testing method used to identify surface defects in 3D printed products. The product is sprayed with a dye, and the dye penetrates any surface defects or cracks. The excess dye is removed, and a developer is applied which highlights any surface defects or cracks.

CMM (Coordinate Measuring Machine)

CMM is a device for the distance of the dimensions of 3D printed products. This machine can measure the product's length, width, height, and other dimensions.

Impact testing machine

An impact testing machine is a device that can test the impact resistance of 3D printed products. This machine simulates the impact of a sudden force on the product and measures the impact resistance of the product.

Ultrasonic testing

Ultrasonic testing is a non-destructive testing method that uses high-frequency sound waves to examine the internal structure of 3D printed products. This can help identify defects or imperfections in the product's internal structure that may not be visible on the outside.

Environmental testing chamber

Environmental testing chambers can be used to simulate different environmental conditions, such as temperature, humidity, and pressure, to test the performance of 3D printed products under these conditions.

Constraints When Testing and Refining 3D Printed Products

There are several potential constraints that may be faced during the testing and refinement processes of a 3D printed product. It is essential to identify potential constraints during the testing and refinement processes of a 3D printed product and develop strategies to overcome them. By addressing these constraints, manufacturers can ensure that they develop high-quality 3D printed products that meet all requirements and are successful in the market. Table 3.4 illustrates the most common constraints.

Table 3.8: Common constraints when testing and refining 3D printed products	
Constraint	Description
 Material limitations	The type of material used in 3D printing can affect the quality of the final product. Certain materials may not be suitable for specific product requirements or may have limited availability or cost constraints.
 Printing limitations	3D printing technology has limitations in terms of size, accuracy, and resolution. This can result in design constraints and may limit the complexity of the product that can be printed.
 Testing equipment availability	Some testing equipment required for physical testing may not be readily available, or it may be too expensive to obtain or operate. This can limit the testing that can be done and may lead to incomplete or inaccurate testing results.
 Time and budget constraints	Testing and refining a 3D printed product can be time-consuming and expensive. Limited time and budget can constrain the amount of testing that can be done, potentially leading to incomplete testing or an insufficiently refined final product.
 Human error	Human error during the testing and refinement processes can result in inaccurate data collection or analysis. It is crucial to have skilled and trained personnel to perform testing and analysis to minimize the risk of human error.
 Intellectual property constraints	The refinement process may require collaboration with other stakeholders, including designers, engineers, and clients. This can create intellectual property constraints that need to be carefully managed to protect the interests of all parties involved.

Exercises

1

Read the sentences and tick ✓ True or False.	True	False
1. 3D printing allows for rapid prototyping.	☐	☐
2. The pre-testing phase involves physically testing the prototype.	☐	☐
3. Testing criteria should be established before beginning the testing process.	☐	☐
4. Developing a testing timeline is not necessary for an efficient testing process.	☐	☐
5. Outsourcing testing to a third-party testing facility is never an option.	☐	☐
6. Analyzing testing results is the first step in the product refinement stage.	☐	☐
7. Iterative design changes are not necessary when refining a 3D printed product.	☐	☐
8. Feedback from stakeholders is not necessary for the refinement stage.	☐	☐
9. Environmental testing chambers can be used to simulate different environmental conditions for testing 3D printed products.	☐	☐
10. 3D printing technology does not have any limitations in terms of size, accuracy, and resolution.	☐	☐

2

Explain the purpose of establishing testing criteria before conducting tests.



- 3** Evaluate the benefits of using 3D printing for prototyping compared to traditional manufacturing methods.

- 4** Assess the importance of a testing report in the refinement process of a 3D printed product.

- 5** Evaluate the effectiveness of the iterative design process during the refinement stage.



6 Describe the importance of documentation in the refinement stage.

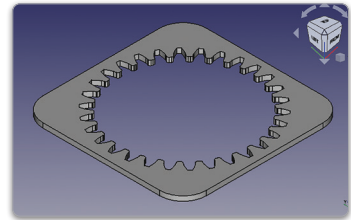
7 Explain how a scanning electron microscope is used during the refinement process of a 3D printed product.

8 Analyze the potential constraints faced when testing and refining a 3D printed product and discuss their impact on the final product quality.

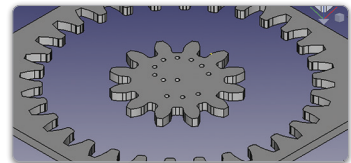


Project

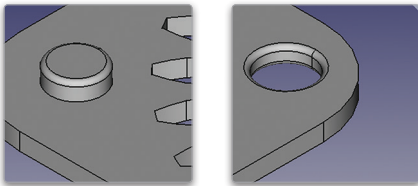
To design the spirograph, you will create a base using the rectangle tool, and you will create a hole in the base using an involute gear.



You will create another involute gear to rotate on the base. This involute gear will have holes in different places to input a pen or pencil to draw different spirographs.

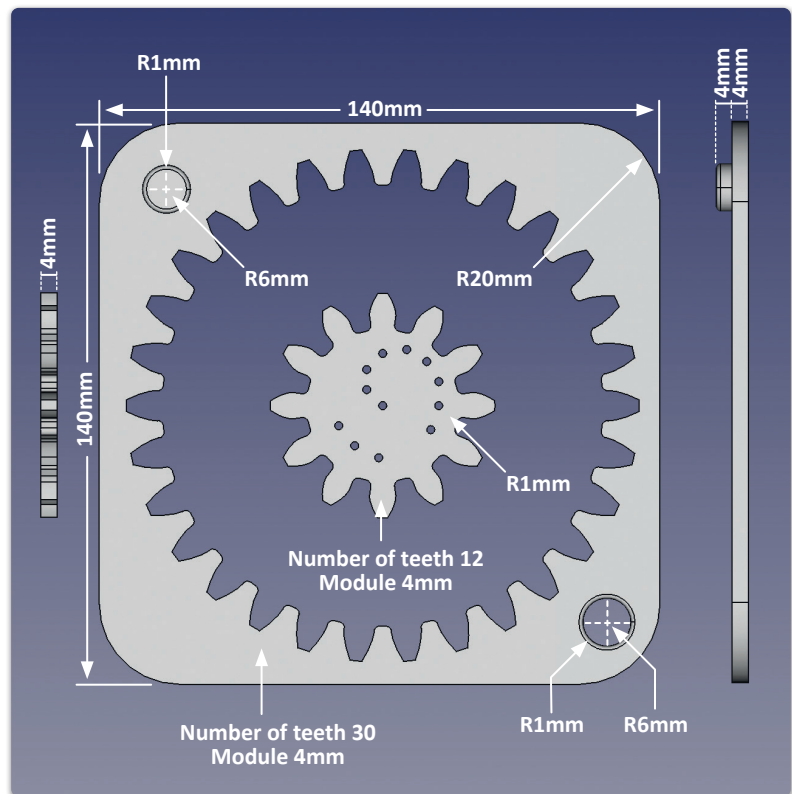


Create a holder and a hole to help you keep the base stable when using the spirograph.



Use the following sketches to design the spirograph.

Once printed, you will mount the two gears together to create the spirograph.



A printed Spirograph.



Printed Base of the spirograph.



Printed Involute gear



Wrap up

Now you have learned to:

- > Analyze the use and the various types of 3D printers.
- > Identify the categories of 3D printing materials.
- > Categorize the applications of 3D printing.
- > Build a 3D printed prototype of an object.
- > Design a pill box with Braille numeric symbols.
- > Use isometric drawing to create accurate visual representations of the product.
- > Use the polyline and pad tools to create intricate details in your design.
- > Outline the phases of testing and refining a 3D printed product.
- > Describe the tools used for testing and refining 3D printed products.
- > Analyze the constraints that are present when testing and refining 3D printed products.

KEY TERMS

3D Inkjet Printing

3D Printing

Additive Manufacturing

Braille System

Human Error

Physical Testing

Pre-Testing

Prototype

Rapid Prototyping

Virtual Testing

