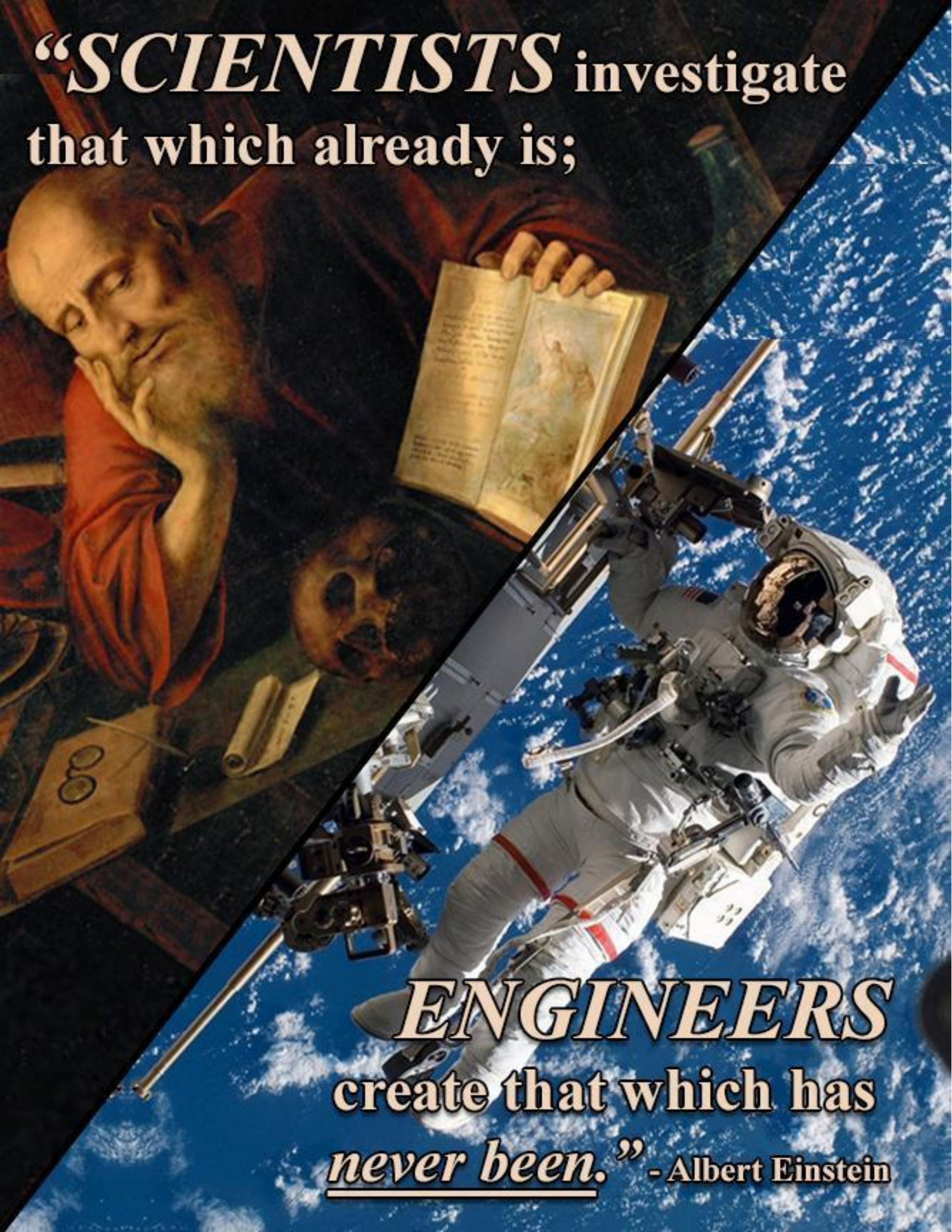

"SCIENTISTS investigate
that which already is;
ENGINEERS
create that which has
never been." - Albert Einstein

Preface

Design Makes Us Human

Why is design important? Everything artificial was designed by a human - The effects of design shape our day-to-day lives. *Design is what sets us apart from other life on Earth.* Non-human animals can communicate, build modest structures and their environments. Some are intelligent and curious, exploring their surroundings and even passing down traditions to their young. However, humans explore and interact with the environment in a way that is unique to our species - **we design ways to do things that have never been done.** Humans explore unknown spaces without knowing what lies ahead; we are the only species to search the ocean for new land, and upon finding it, invent new ways of changing it. Looking towards the future, humans are the only species from Earth with the potential to inhabit other planets.

Elephants are highly intelligence and pass down knowledge to younger family members about how to survive in the harsh wild. Despite this, you are unlikely to see an Elephant Manhattan

Our obsession with novelty and progress has not been without consequences. History has seen a long series of successful (and often not) experiments that were necessary to design the complex ways that we live our lives. But while an elephant may be able to remember its way home during rush hour, there are no elephant cities from which to drive home. No team of beavers could reconstruct the Hoover Dam, nor could a parrot improve the writings of Leo Tolstoy. Cities, dams, and the culture-rich worlds we inhabit have only been designed by humans. Through thoughtful planning and deliberate action, design lets us adapt our surroundings to suit our lifestyles and make tools to change how we live. *Design is what makes us human.*

What Is Design, and How Is It Different from Other Activities, Like Art?

Design can change our world in many ways. Thus, ***design*** can mean many different things across a wide range of contexts. Here, we focus on the ***design process***, the complex and iterative set of steps taken by the designer to **create an object or experience that solves a problem or meets a goal**. Problems often have specific goals and ways of objectively measuring performance. For example, consider a common real-world engineering design problem: traveling across bodies of water. Cities are often built along the edge of water, leaving the local economy and community dependent on access to consistent and safe travel across the water. This gives the designer a clear goal: to design a structure that allows travel across the water with minimal risk and inconvenience. A common solution is to build a bridge (often a series of bridges) to allow safe and easy travel. However, there are many external constraints to consider. For example, natural water formations and existing infrastructure place strict constraints on bridge location, length, and width. Once the design process is complete, bridge safety and usage can be objectively measured to show how well the solution achieved the goals. The designer must also consider aesthetics, but reliability, cost, and efficiency are often the most important considerations.

The focus on objective measurements of solutions to real-world problems makes the design process unique from similar activities, such as art. The artist has very few, if any, objective requirements. In other words, there are often no “rights” or “wrongs” when creating art. Where a designer may focus on objective requirements and external constraints, an artist’s greatest drive is often to communicate ideas or themes that they feel are important to themselves, or a broader audience. The artist must deal with external constraints, such as canvas size or material cost. However, when compared to design, art places a higher emphasis on internal, subjective constraints.

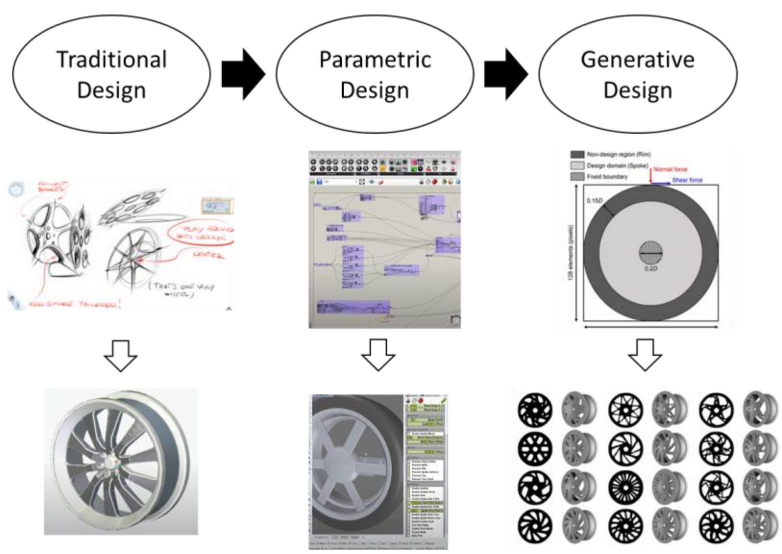
Left*: Design often has clear goals to achieve and objective ways of measuring performance. A bridge’s goal is to allow travel across a body of water, and performance can be measured via weight limits and safety records.* ***Right****: The goal of many art projects is to express emotions, themes, and ideas that are important - even if just to the artist. This is often seen through the unique style developed by many street artists.*

What Are the Different Ways to Design?

There are many different ways to accomplish a goal, and design is no exception! **Paradigms** (Greek; loosely translated as *pattern*) are collections of ideas that shape the way we think and act. A **design paradigm** is a framework that provides a foundation for understanding and approaching the design process. Paradigms guide how the designer thinks and acts throughout the design process, and **different paradigms may offer vastly different solutions to the same design problem**. There are three major paradigms to engineering design: **Traditional, Parametric,** and **Generative**.

1. **Traditional design (TD)** follows established practices and emphasizes human cognition and action. It often involves manual sketching, prototyping, and iterative refinement. To meet predefined requirements and constraints, the designer must rely heavily on their expertise and intuition.
2. **Parametric design (PD)** uses computational algorithms and parameters to guide the design process. Designers define relationships between variables to computationally generate a corresponding design. This approach is highly flexible and allows the designer to explore multiple design possibilities by changing the parameter relationships. This results in adaptable and optimized solutions.
3. **Generative design (GD)** employs artificial intelligence to algorithmically generate up to thousands of design options for the human designer. Design goals and constraints are defined, and the computer generates and evaluates numerous design iterations automatically. This method often generates unconventional and innovative solutions not typically conceived through traditional design methods.

The relationship between these paradigms can be seen as a progression from traditional design to parametric design, and finally to generative design, as shown in the figure on the right. Such a progression is a natural outcome of science and technology development. Each paradigm builds upon the previous one, incorporating computational elements and expanding the possibilities for design exploration and optimization. However, it's important to note that these paradigms are not mutually exclusive, and designers often use a combination of them. We will focus on each of these paradigms in more depth below, starting with traditional design.



Traditional Design

We will first focus on **Traditional Design**: the established principles and practices for conducting engineering design. This paradigm emphasizes human activities, such as manual sketching, to explore design possibilities. Traditional design relies on the designer's expertise, experience, and intuition to generate solutions based on predefined requirements and constraints. A key difference between the design paradigms is in how the designer engages with the **Design Space** and the **Objective Space**.

The Design and Objective Spaces

The **Design Space** is the multidimensional space that represents all possible design options or solutions for a given problem or task. It represents the entire range of potential design configurations, parameters, and variations that can be explored. The design process focuses on exploring and exploiting the design space to search designs that meet the criteria.

The **Objective Space** represents the performance or evaluation criteria used to assess and compare different designs. It is typically defined by the goals, objectives, or metrics that a design should meet. *For example, if my goal is to stay healthy, one of my objectives might be to control my weight, and its metric would be my body weight (in kg or lb)*. The objective space provides a framework for evaluating designs based on important criteria and comparing different designs based on their performance.

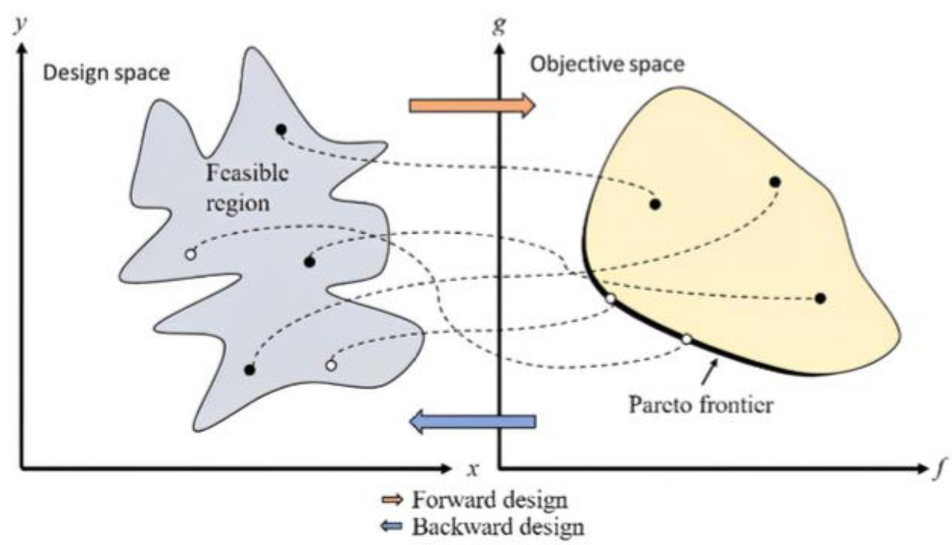


Figure 1. *A two-dimensional example of the design and objective spaces.*

Designers using the traditional design paradigm take a different **design direction** than designers using parametric or generative design paradigms. As shown in Figure 1, **Forward Design** occurs when the designer works from the design space to the objective space. Designers begin by extrapolating values for parameters from their previous experience and then examine whether these chosen values align with the desired objectives. TD and PD often follow a forward design direction.

This is different from **Backward Design**, which is often adopted in GD. In backward design, design moves from the objective space to the design space. Designers start by defining the objectives for generative design software based on the specified criteria and constraints and then use the software to find the values of the parameters that meet the objectives. However, since design iterations will occur in both ways of design, the forward and backward directions described are the concepts more emphasized at the level of design thinking or how we mentally approach a design problem from the beginning.

1.1 TD: Problem Definition

Imagine you're designing the wheels for a new car. What is the first step you would take? Would you immediately start sketching your sleek and creative ideas, or instead would you ask the client what style they want?

Figure 2. *Now imagine you have designed the sturdiest truck wheel ever (left) but only to realize <u>your client wanted a sports car (right)!</u>*

The designer starts by understanding the specific problem that the design should solve. This includes clearly defining the **objectives** to achieve and identifying any **constraints** that the design must work within. *Should it be sturdy or lightweight? How much is the budget?* These and similar questions can often be answered by talking to the client, but not always! In some cases, the client is unaware of the underlying problem that needs to be solved and may only be able to communicate the symptoms of the problem (e.g., "The current wheel is too heavy," or "The wheel is ugly"). This would require the designer to closely analyze the problem to deduce the underlying key variables and constraints (Figure 3).

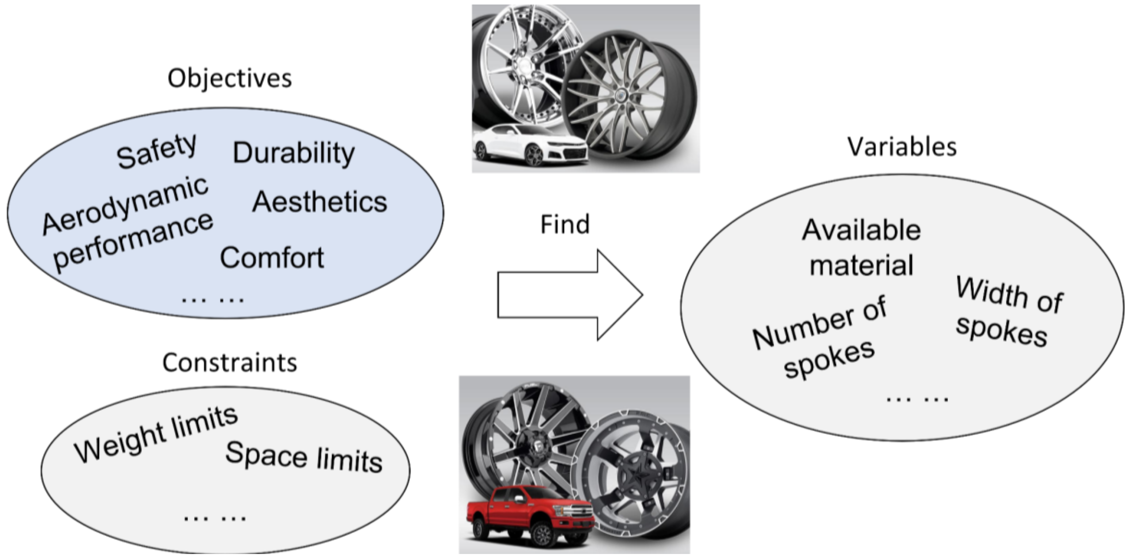


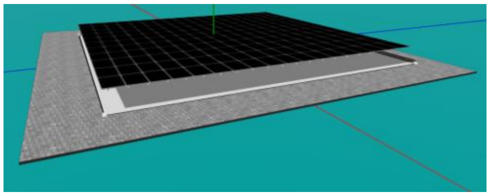
Figure 3. Example of the car wheel design for Problem Definition. *This table specifies the customer requirements, technical requirements, and engineering specifications. This can serve as a reference guide for the design process and determine which designs get created and selected.*

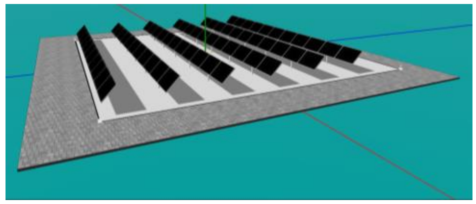
Recognizing the key **design variables** and **constraints** allows the designer to define the **design space**, which contains all possible design solutions. *For example, one possible solution is aluminum wheels with five spokes; another solution may be steel wheels with six spokes.* Next, we will go through a practice example to experience these ideas at work.

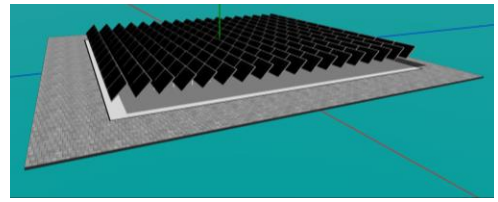
Practice example: Solar farm design

Solar farms are power stations that use a large number of solar panels to produce electricity. See below for some real-world examples:

1. Below are a few different computer models of solar farm designs in a rectangular plot:



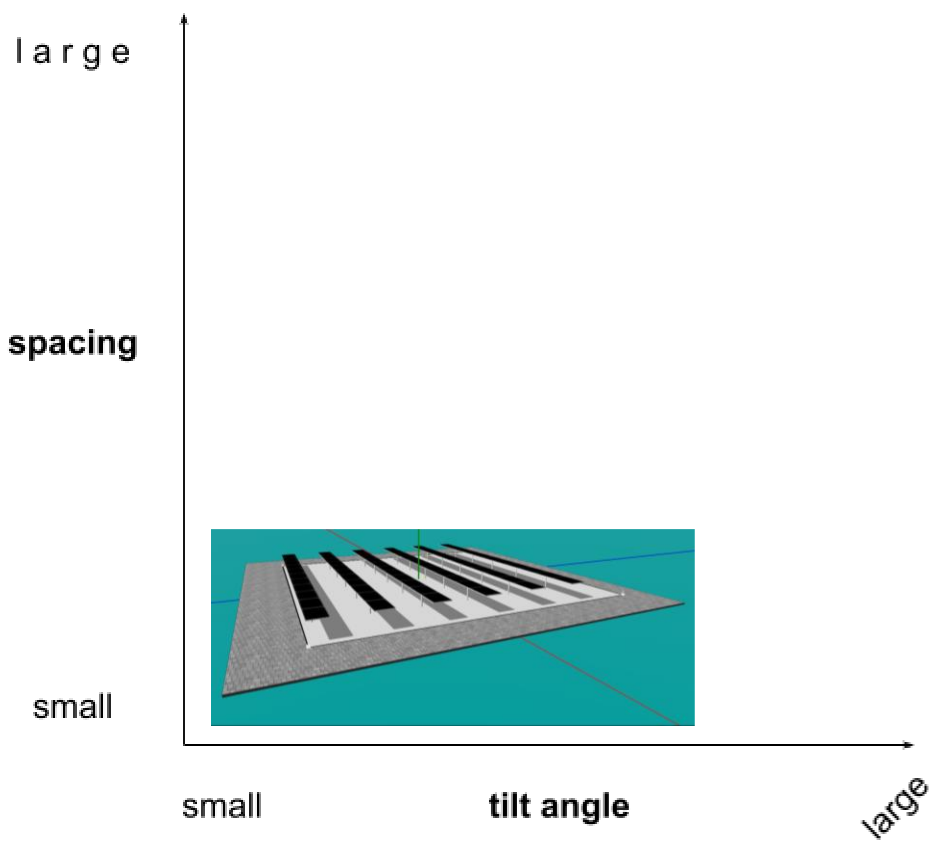




These designs can be categorized based on two **design variables**:

a. The **tilt angle** of the solar panels,
b. The **spacing** between solar panels.

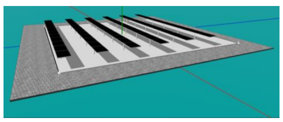
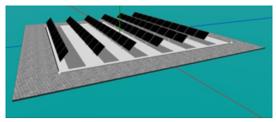
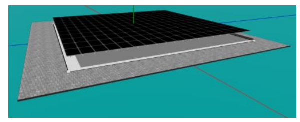
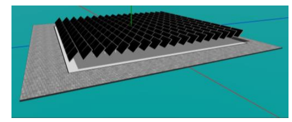
Identify where each design belongs in the design space below and drag the three images above to appropriate locations. One example (a flat and sparse design) has been provided for you.

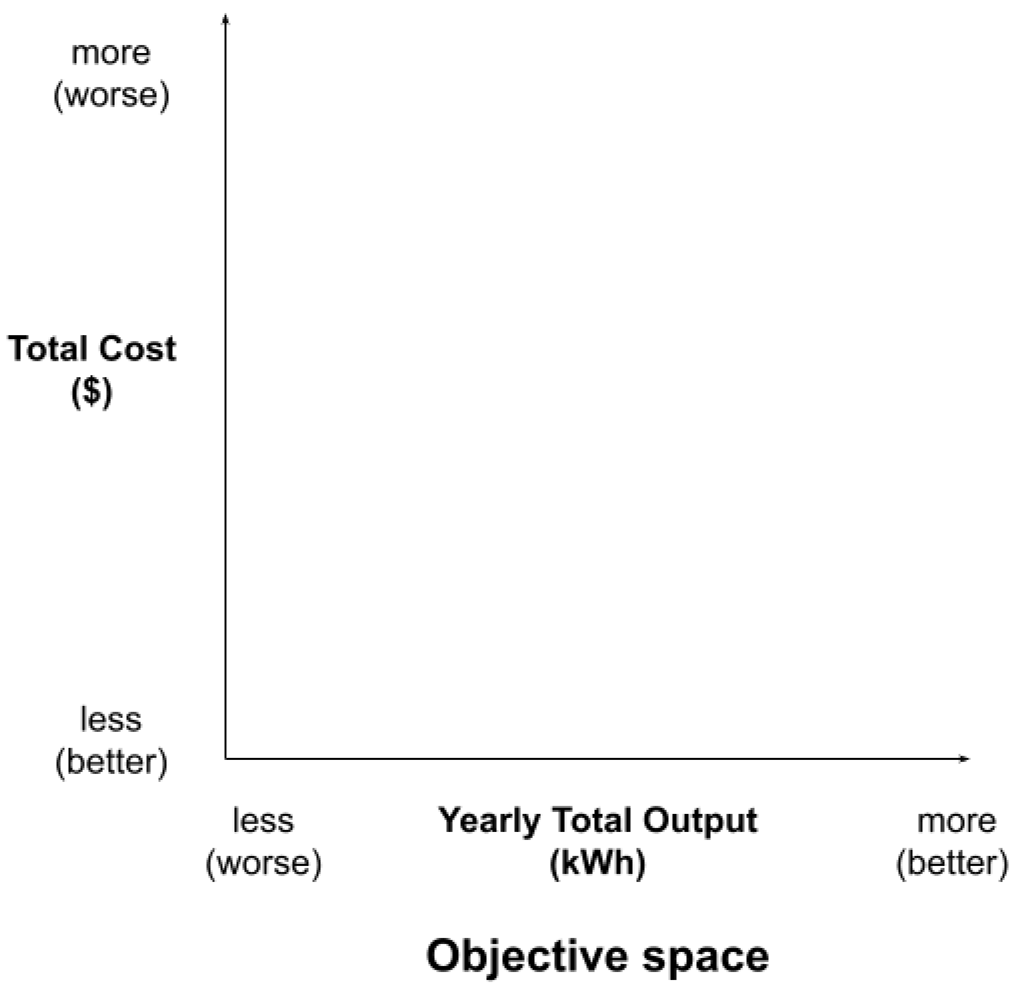


Design space

2. Despite the endless possibilities, solar farm design is far from arbitrary: the main objective is often to achieve the **maximum energy output** under the given **constraints (such as land boundaries, budget, and location)**. For example, consider these two objectives:
    - Maximize the total energy output of all solar panels,
    - Minimize the total cost of all solar panels.

    By dragging the images below, try to **guess the performance** of the same four designs as above and **identify where they might fall** along the **objective space**.



1.2 TD: Exploration

We will continue with our car wheel example. Imagine you have decided that material and spoke width are two important variables of your car wheel design. So, should you use wide aluminum spokes, or thin steel spokes?

Once you have defined the design space and considered how different variables may affect performance, you can enter the next stage - **Exploration**. The goal of this stage is to identify how the design variables and constraints are related to the objective(s) by generating different design concepts that may each achieve the objective (Figure 4.). Therefore, exploration often involves two major tasks: 1) the identification of all possible design variables and constraints, and 2) the generation and synthesis of all possible designs in the design space defined by the design variables and constraints.

A common strategy for exploring the design space is to **diverge** and generate designs that are as different from each other as possible. For example, two main objectives in car wheel design are wheel strength and wheel speed. First, think about designing a wheel optimized for strength. *What are the strongest and most durable materials? How wide should the spokes be?* In this case, the designer may choose a heavy material to add strength and utilize a wide spoke width to distribute pressure more equally along the inside of the wheel.

Now, imagine you are designing a wheel optimized for speed. *How would this be different from the previous wheel? Are lighter materials available? How can aerodynamics be improved?* A lighter material will reduce the weight of the vehicle but may sacrifice strength. Exploring the "edges" of the design space will often help the designer understand how these variables impact design performance.

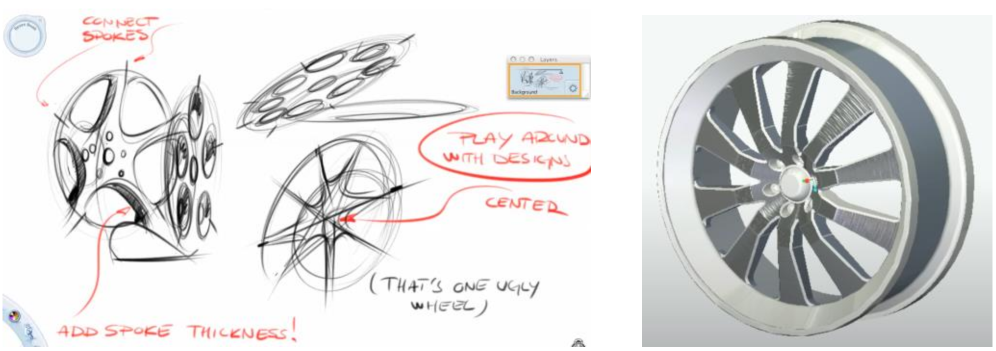
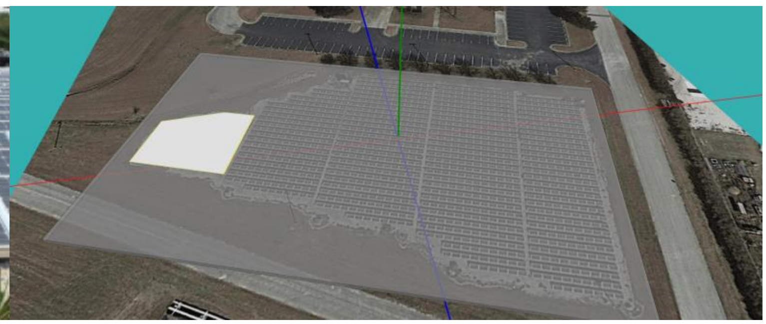


Figure 4. *Exploration in car wheel design.* ***Left,*** *Designers often start by sketching various concepts and ideas. They explore different shapes, patterns, and textures that may enhance the performance or aesthetics of the wheels.* ***Right,*** *Designers translate their conceptual sketches into digital models using computer-aided design (CAD) software, where they can further experiment with different dimensions, materials, and finishes.*

Practice example: Solar farm design

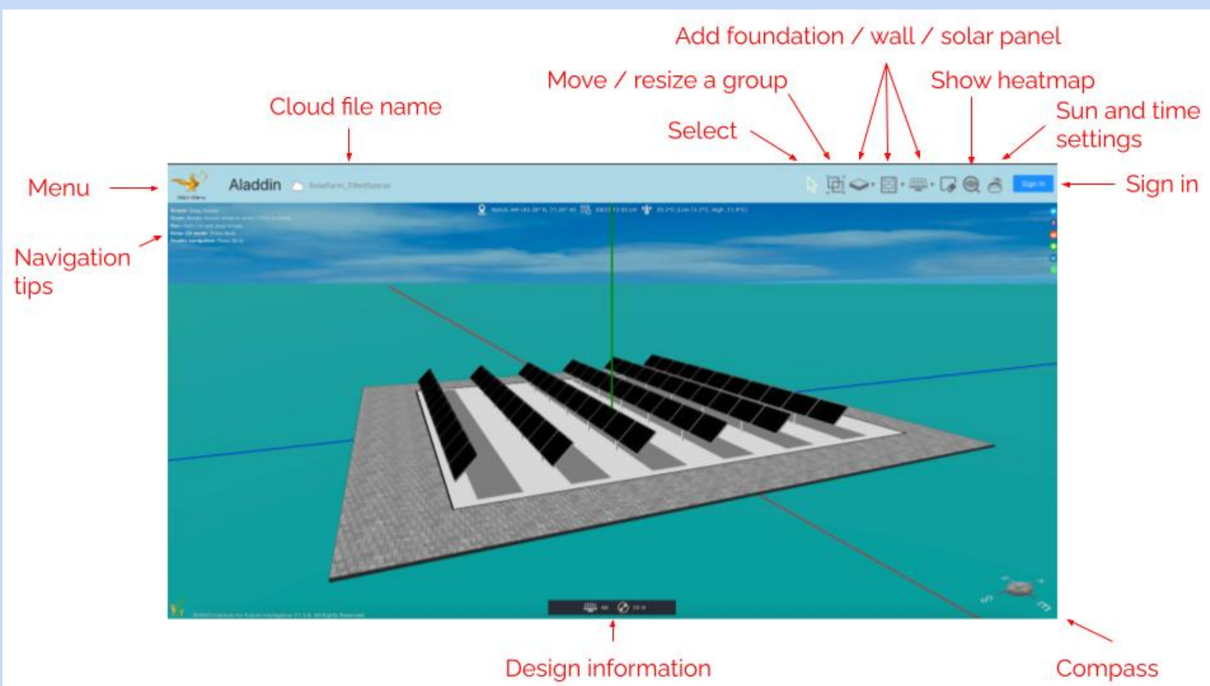
Previously, you gained some initial understanding of the definition of the solar farm design problem by looking at its design space and objective space. This next practice example will help you explore the design space in a more realistic context.

UT Austin is installing a solar farm at the Pickle Research Field and needs your help creating the best design. Most of the design has already been completed, but a small part of it is still under construction. **You will use a design tool called *Aladdin* to explore the design space and finish designing the rest of the solar farm!**

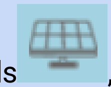
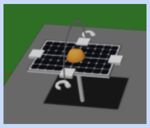
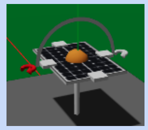
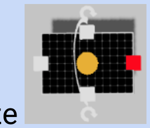
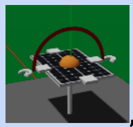



[Click here to open the *Aladdin* model of the Pickle solar farm.]

Aladdin: Quick Start



When you open the *Aladdin* model, you can:

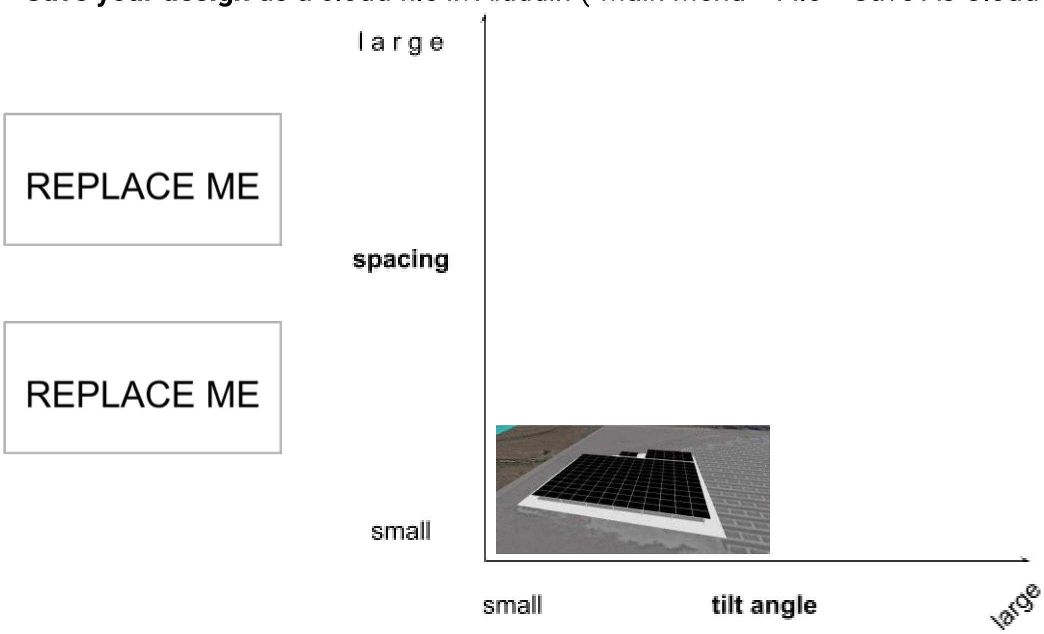
- add new solar panels ,
- move , rotate  and resize  solar panels,
- change their angles , copy and paste 

new panels.

Read the *Aladdin* Reference Slides (also in the Box folder) for more tips on how to navigate the software.

Use this chance to explore a few different designs. For example, a flat and dense design has already been provided for you. First, **try to create a design that is the opposite**, with *large tilt angles* and *large spacing*.

- **Take a screenshot** (“Main Menu > File > Take Screenshot”)
- **Replace the first image placeholder below** (Right click > “Replace image > From file…”)
- **Move the screenshot** onto the appropriate location on the design space below.
- **Save your design** as a cloud file in *Aladdin* (“Main Menu > File > Save As Cloud File…”)



Design space

Great, now try again! Can you use the same template to create **another design that is different from either of the previous two?** Take another screenshot, replace the other image placeholder, and place it in the design space above. Save your second design as a cloud file as well.

3. Copy the *Aladdin* links to your two designs and document them in the table below.

	Design 1	**Design 2**	**Design 3**
Variable: Tilt angle	small	large	*[Insert your own design choices]*
Variable: Spacing	small	large	*[Insert your own design choices]*
Link	https://institute-for-future-intelligence.github.io/aladdin/?client=web&userid=JmlYdhia1fROj6WNd8dDZwwtW8Q2&title=Pickle%20Design_SW19_TD_v2_Ex_Max	*[Save your design as a cloud file and insert the Aladdin link here]*	*[Save your design as a cloud file and insert the Aladdin link here]*

Congratulations! You have just finished your very first solar farm designs.

1.3 TD: Evaluation

Some designs will be better than others. But how do you know if aluminum wheels are more durable than steel wheels, or less durable? The first goal of the **Evaluation** stage is to analyze the design performance to determine if the objectives and constraints are satisfied (Figure 5a). Here is where things get tricky: Each design may perform better at some objectives and worse at others. *There may be a* ***trade-off*** *between the strength of a truck wheel and the speed of a race car wheel.* How do designers make a choice then?

Designs may either be **dominated (**by other designs) or **non-dominated** (Figure 5b). Dominated designs perform worse in all metrics. *Imagine a third car wheel design that is both weaker than the truck wheel and slower than the race car wheel.* A non-dominated design performs better in at least one objective than every other design. *In the previous example, both the truck wheel and the race car wheel are non-dominated and are worthy candidates.* **The second goal of Evaluation is to identify the non-dominated designs and remove dominated designs.**

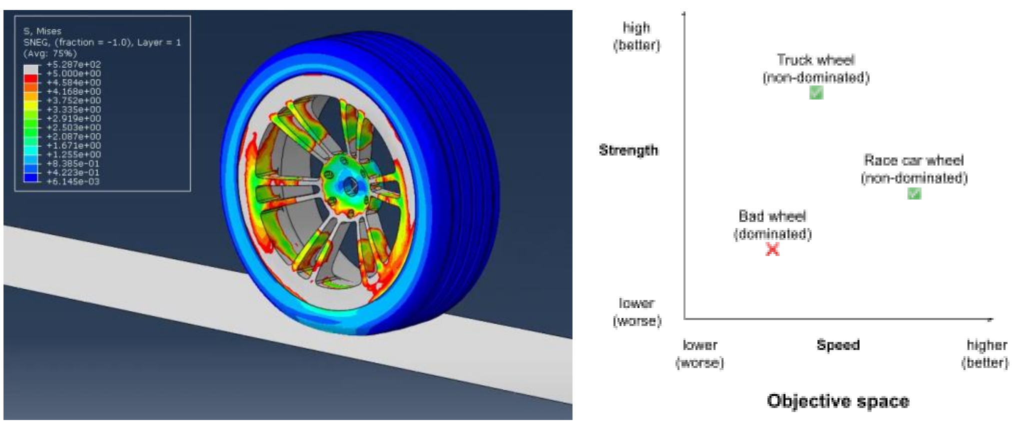
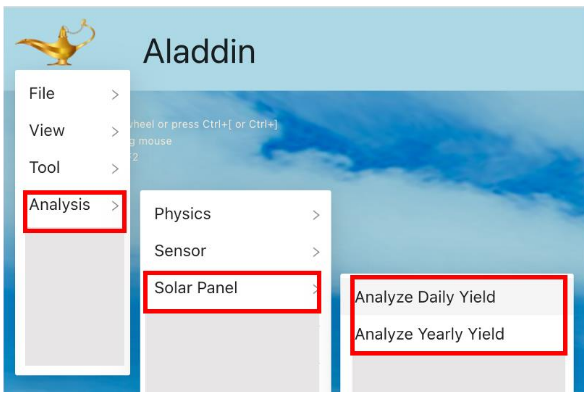


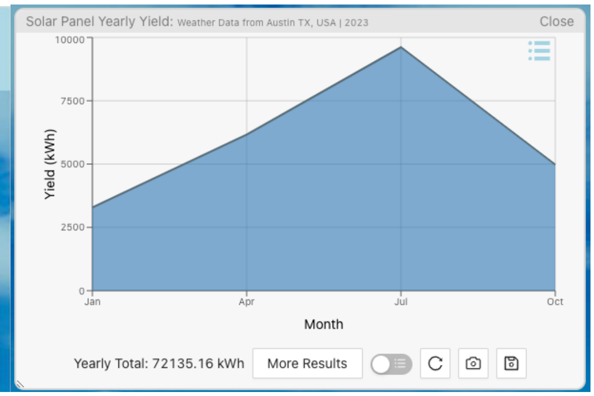
Figure 5. *(a) Evaluation of a car wheel design using computer-aided engineering (CAE) software. (b) A comparison of three car wheel designs in the objective space.*

Some goals can be *objectively* measured, like the safety, durability, and aerodynamic performance of a car wheel, often with the help of computer-aided engineering (CAE) software. However, *subjective* goals like aesthetics, beauty, and creativity cannot be easily coded into a computer model. **Thus, design aesthetics are often left to the discretion of the human designer, who must balance beauty and performance.**

Practice example: Solar farm design

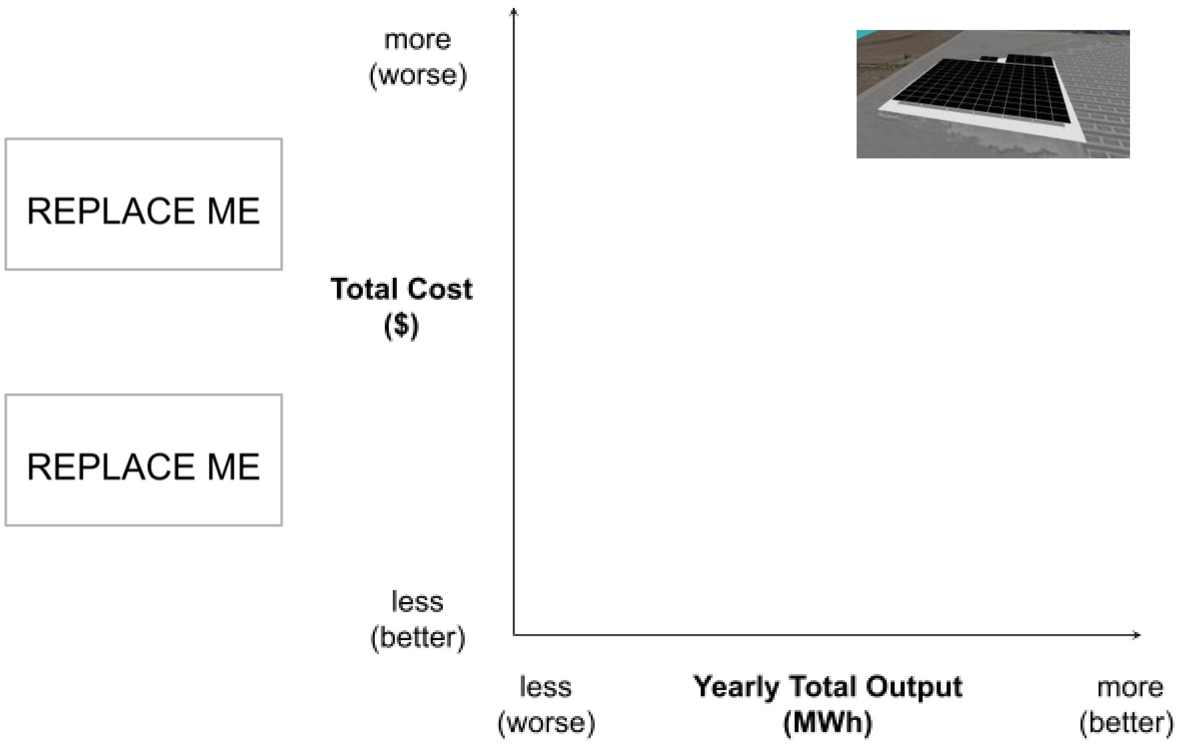
4. Take this chance to evaluate the two solar farm designs you generated earlier. Follow the instructions to analyze each design and **record the results in the table below.**





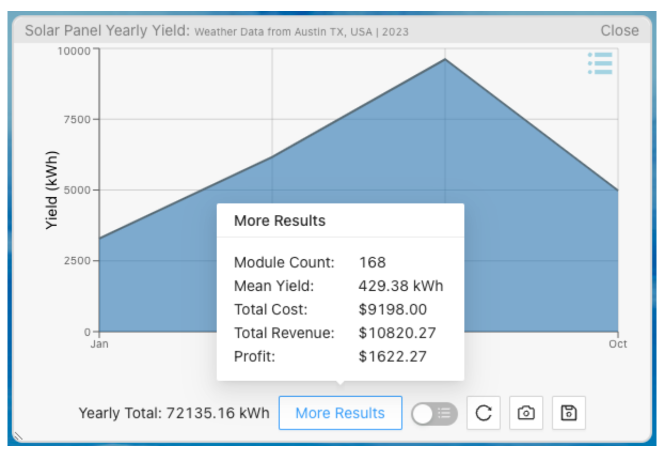
	Design 1	**Design 2**	**Design 3**
Variable: Tilt angle	small	large	*[Insert your own design choices]*
Variable: Spacing	small	large	*[Insert your own design choices]*
Aladdin link	Link	Link	Link
Screenshot			
Objective: Yearly total output (kWh)	72135.16		
Objective: Total cost ($)	9198		
Objective: Profit ($)	1622.27		
Objective: Yearly average output (kWh)	429.38		

5. Map the three designs onto the objective space below. **Design 1** (high energy output and high cost) has already been provided as an example.



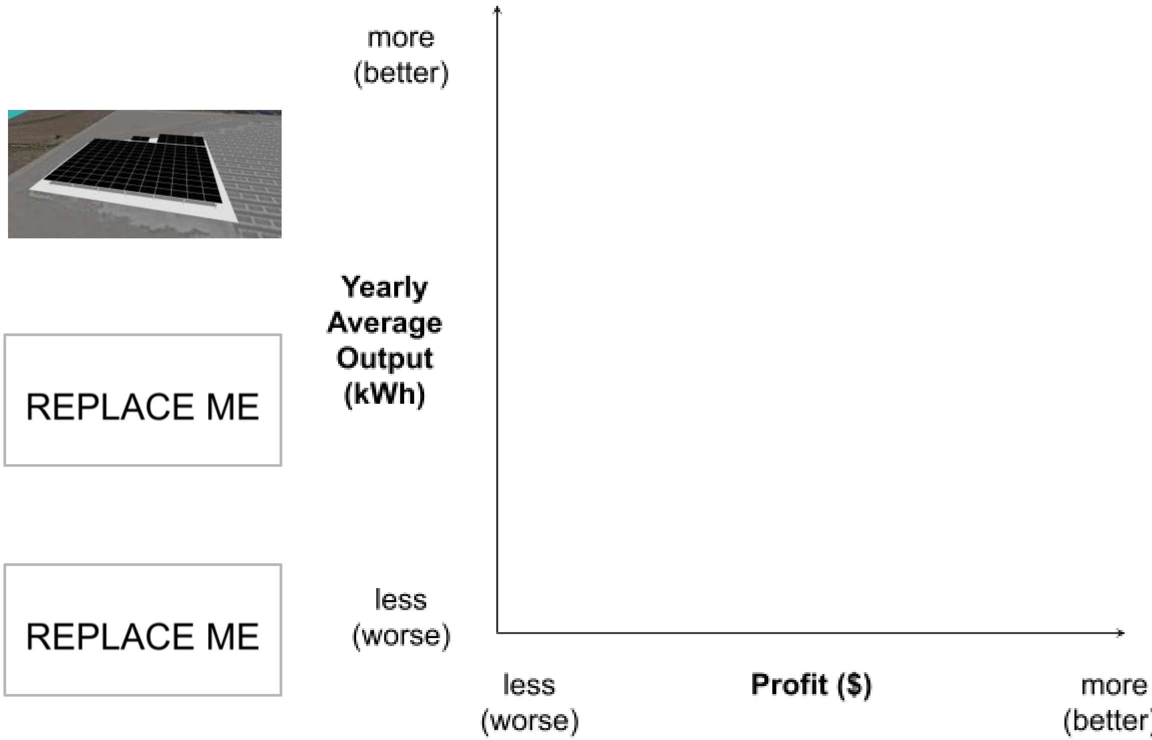
Objective space

Now that we have evaluated all three designs, are we ready to declare which is better? Well, not always. For one thing, designs with a higher output tend to use more solar panels, which incur a higher cost by nature. Fortunately, there are often **multiple objectives or metrics**, with which to evaluate the designs. In the case of solar farm design, *Aladdin* also provides additional analysis results, including:



- **Yearly Profit** = Total Revenue - Total Cost
- **Yearly Average Output (or Mean Yield)** = Yearly Total Output / Module Count

6. Map the three designs onto a different objective space below, including design 1. Since the objectives have changed, be aware that their relative positions may change as well.



A different objective space

7. Which design has the most profit (and is therefore non-dominated)?

8. Which design has the most yearly average output (and is therefore also non-dominated)?

9. Are the remaining designs non-dominated (i.e., better in at least one objective than any other design)? Or are they dominated by any design?

1.4 TD: Iteration

Engineering design is a complex task that often requires the designer to cycle through the design process to refine a concept towards the goals identified earlier. The concepts generated during **Exploration**, and the insights and comparisons from **Evaluation** will inform the designer as they continue to solve the problem. The goal of **Iteration** is to refine the designs to eventually achieve the goal(s) by optimizing alternative concepts and comparing them against each other. By doing this, designers can evaluate the strengths and weaknesses of different concepts to build a deeper understanding of the design space and the objective space.

The key role of the designer is to incorporate feedback and insights from testing and evaluation into future exploration. By repeating the process and making adjustments to address any issues, a satisfactory solution can be reached. Designers can use **Design of Experiments (DOE)** to change one variable at a time and evaluate the results to determine cause-and-effect relationships. *For example, if one of your designs uses 6 spokes, what about 7 spokes? 8 spokes?*

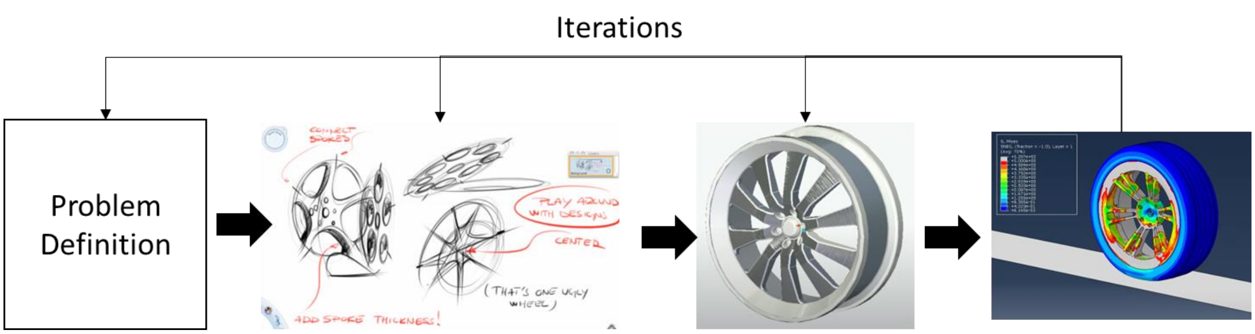
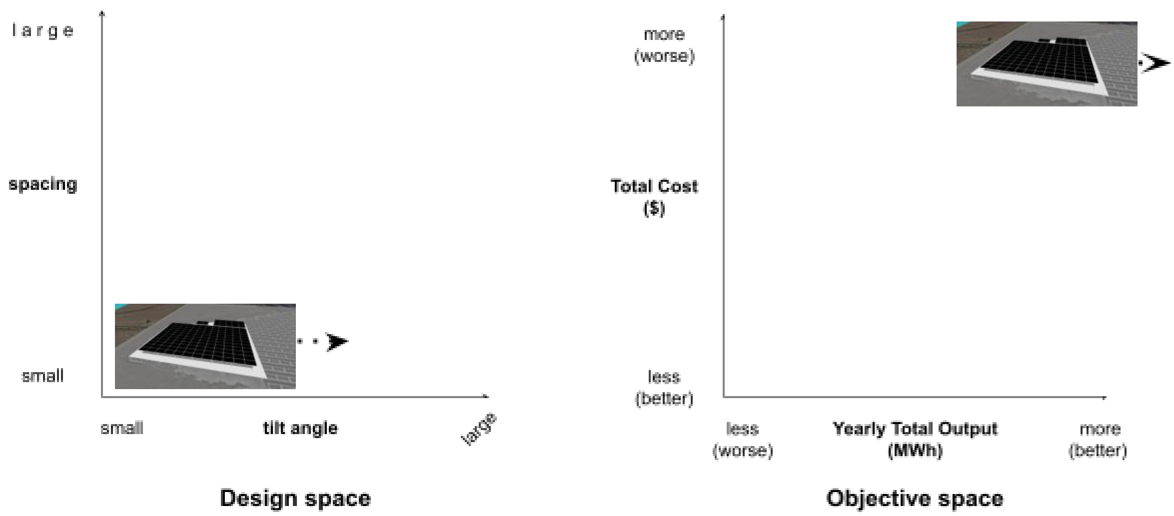


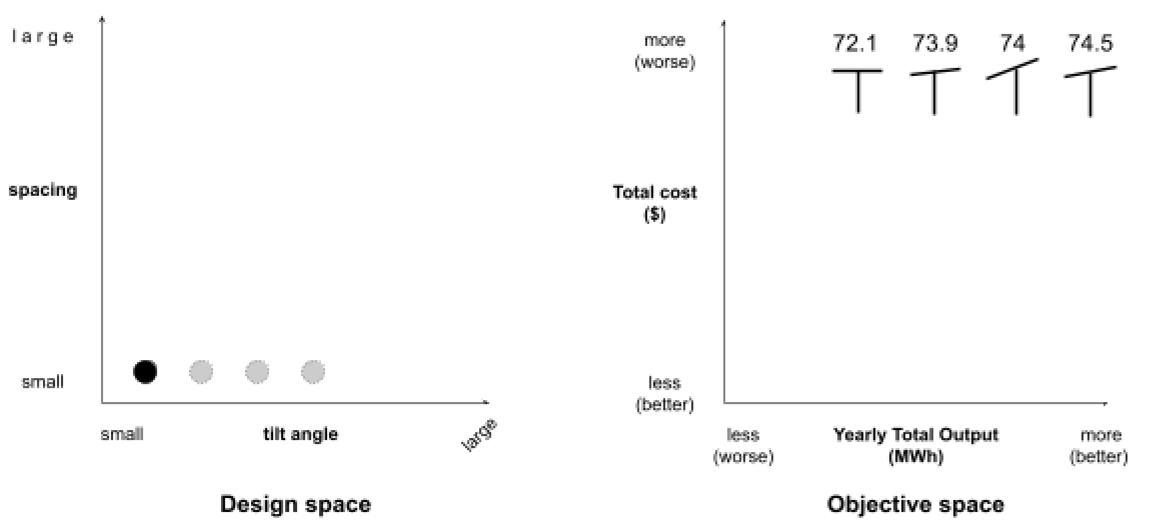
Figure 6. *Iteration in car wheel design. Through a series of iterations, designers cycle between the design exploration, evaluation, and (sometimes) the problem definition stages to continually refine and enhance the concepts until they reach the optimal design. The optimal design is the one that best addresses the problem, satisfies user needs, and meets the desired objectives while considering constraints such as cost, manufacturability, and aesthetics. This iterative process allows for continuous improvement, ensuring that the final design is well-considered, effective, and meets the desired goals.*

Practice example: Solar farm design

The example design with a small tilt angle and large spacing may already be non-dominated, but how can we further improve it? One idea is to change only the tilt angle, so we can explore its nearby design space bit by bit. The reasoning is that if we tilt the solar panels more towards the Sun, then we may increase the total energy output without increasing the cost.



But how much should we change the tilt angle? After several iterations, we may find a sweet spot around 20º that produces the most energy output, and neither a higher tilt (like 30º) nor a lower tilt (like 10º) has a better performance.

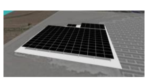


At this point, we can include such a design with both the original small spacing and an improved 20º tilt angle as one of the final design candidates.

It’s your turn to improve your previous designs by iterating a few more times. Here are your options in *Aladdin*:

- Add new solar panels,
- Delete existing solar panels,
- Move, rotate, and resize solar panels,
- Change the angle of solar panels,
- Copy and paste solar panels.

10. In Design 2, the solar panels are already tilted towards the Sun, but there is too much space among solar panels. **Can you iterate on Design 2 by changing the spacing between solar panels while keeping the same tilt angle?**
    - Copy the green table from page 17 into the green table below.
    - Save your best iteration as a cloud file, so you can attach a link in the blue table.

	Design 1	**Design 2**	**Design 3**	**Design 1.1**	**Design 2.1**	**Design 3.1**
Variable: Tilt angle	Small (0°)	large	*[Insert your own design choices]*	**Larger (20°)**	large	*[Insert your own design choices]*
Variable: Spacing	small	large	*[Insert your own design choices]*	small	**smaller**	*[Insert your own design choices]*
Aladdin link	Link	Link	Link	Link	Link	Link
Screenshot (optional)						
Objective: Yearly total output (kWh)	72135.16			74474.07		
Objective: Total cost ($)	9198			9198		
Objective: Profit ($)	1622.27			1973.11		
Objective: Yearly average output (kWh)	429.38			443.30		

11. Which of the six designs in the table above are now non-dominated in terms of **profit** and **average output**?

12. Which design achieves the best balance between a high **profit** and a high **average output**? Can you briefly explain why in 1-2 sentences? (The answer can be subjective.)