Traditional Design

We will first focus on **Traditional Design**: the established principles and practices for manually 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 for 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 grow a garden, one of the objectives might be to control the amount of water I use, and the metric would be volume of water (Liters/gallons)*. The objective space provides a framework for evaluating designs based on important criteria and comparing different designs based on their performance in these criteria.

Designers using the traditional and parametric design paradigms take a different **design direction** than designers using generative design. 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.

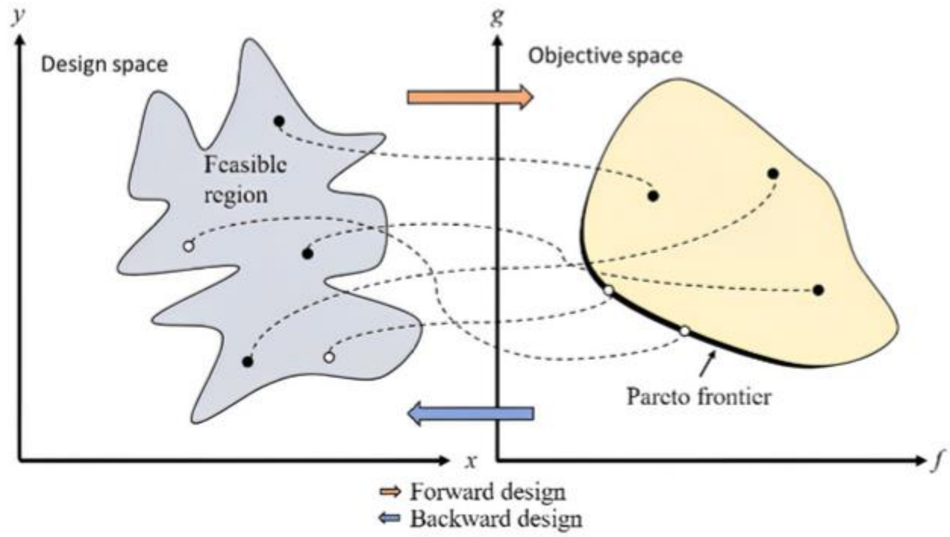


Figure 1. *A two-dimensional example of the design and objective spaces.*

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 generally begin 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, forward and backward design are general approaches to the early design phases as later stage iteration will occur in both directions.

1.1 TD: Problem Definition

Imagine you are designing the wheels for a new car. Think about the first step you would take - Would you immediately start sketching your sleek and creative ideas, or ask the client what style they want?

Figure 2. *Now imagine that you have designed a sturdy and heavy truck wheel (left), only to realize that your client wanted a sports car (right)!*

The beginning of the design process requires the designer to understand the specific problem that the design solution should solve. This includes clearly defining the **objectives** to achieve and identifying any **constraints** that the design must work within. For example, a designer would ask: *Should the car wheel be sturdy or lightweight? How much is the budget?*

Design **objectives** are qualities that the client wants the finished product to possess. In some cases, these objectives are measurable performance criteria. Other design objectives may be more subjective. For an engineer tasked with designing a new car wheel, possible design objectives include safety, durability, aerodynamic performance, aesthetics, and comfort. Some of these objectives can be quantified, e.g., wheel durability can be measured in miles, and a client may request a minimum lifespan of 300,000 miles. Other objectives, like aesthetics, cannot be quantified. If a client states that they want a wheel that "looks cool on my new sports car," the designer is required to make subjective judgements on the design aesthetics.

Design **constraints** are limiting criteria that restrict the possible range of designs. Constraints may be imposed by a wide range of factors, including performance, cost, safety, environmental regulations, or other considerations. Their impact is to limit the designer to work within certain regions of the design space. Designs that fall outside this region, i.e., violate the constraints, will be unacceptable to the client or problem context. For example, weight and space are key constraints in car wheel design. The client may place constraints on the weight limit (e.g., 65 lbs.), wheel diameter (e.g., 20 in.), and/or the wheel width (e.g., 9 in.).

Defining the objectives and constraints often begins by talking to the client, but this may not always be helpful. 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).

Variables are characteristics of the design that are manipulated by the designer as they explore the design space to create a set of potential design solutions. Returning the car wheel design example, potential variables include the number of spokes, the width of these spokes, and the material(s) that the wheel is made of. The designer can create a theoretically infinite number of design alternatives by changing these and any other relevant variables.

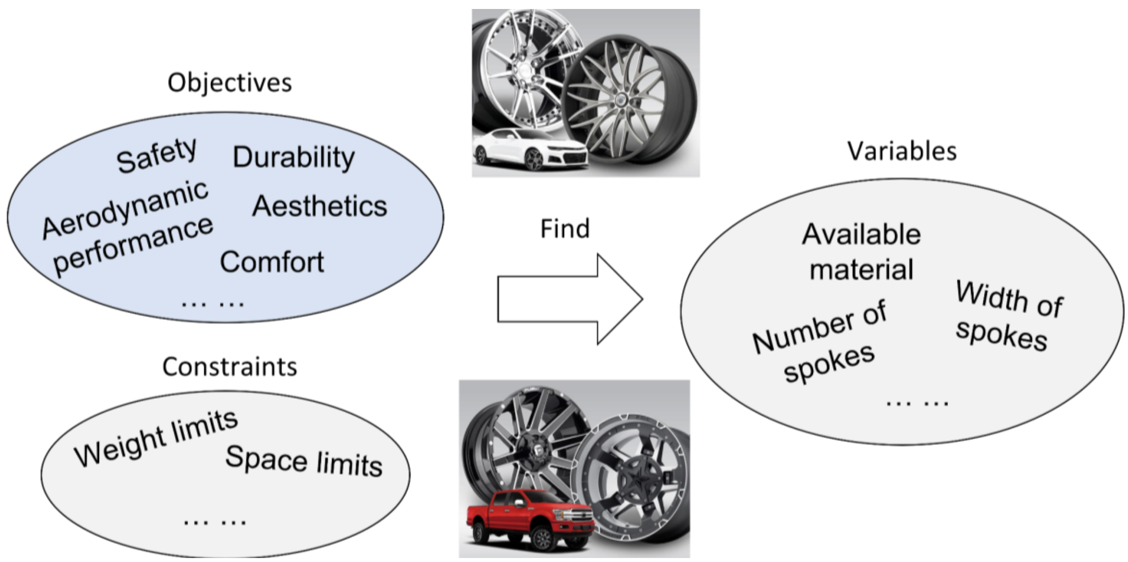


Figure 3. Example of the car wheel design for Problem Definition. *This table specifies the customer requirements, technical requirements, and engineering specifications. This can serve as a reference guide for the design process and determine which designs get created and selected.*

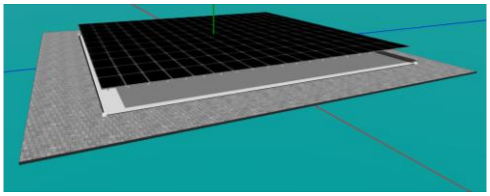
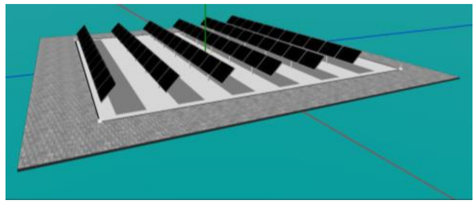
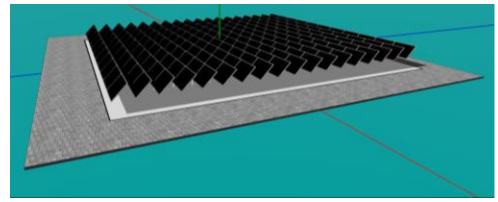
Recognizing the key **design variables** and **constraints** allows the designer to define the **design space**, which contains all possible design solutions. *For example, one possible solution is aluminum wheels with five spokes; another solution may be steel wheels with six spokes.*

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:

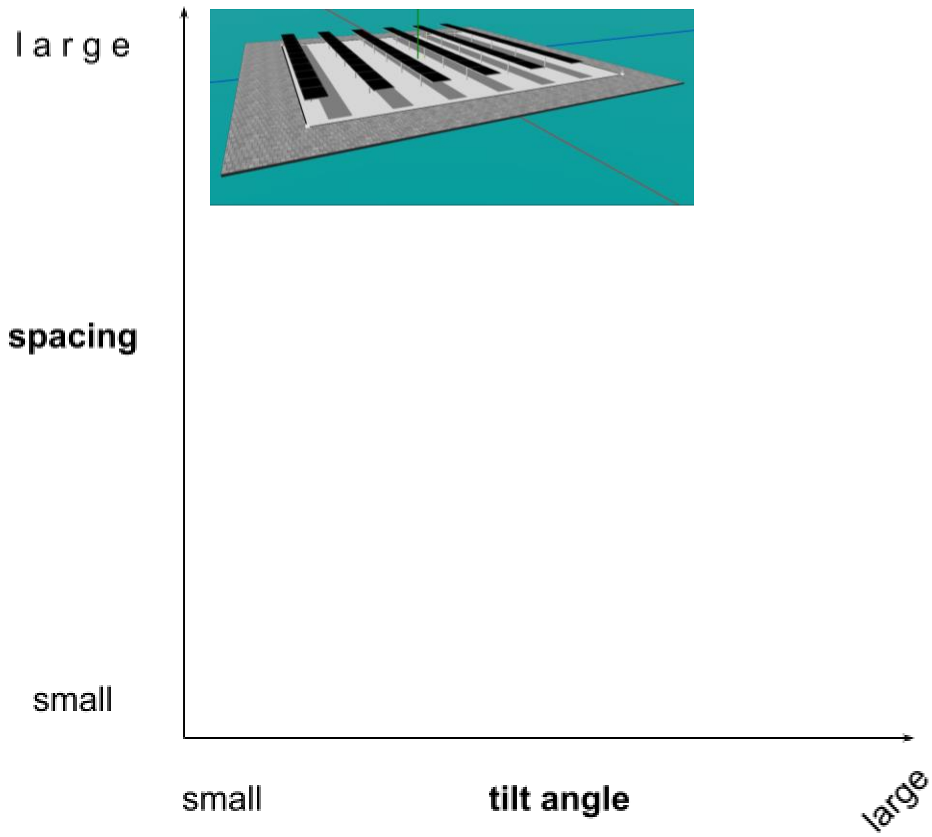
1. Below are a few different draggable images of computer models of solar farm designs in a rectangular plot:

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

a. The **tilt angle** of the solar panels (small angle being flat and large angle being vertical),
b. The **spacing** between solar panels.

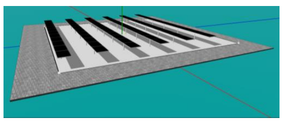
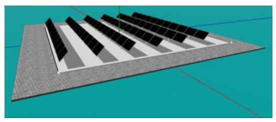
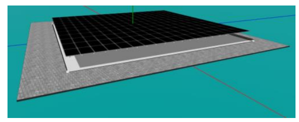
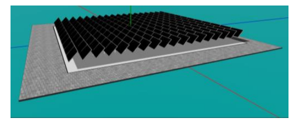
Identify where each design belongs in the design space below and drag the three images above to appropriate locations. One example (a flat and sparse design) has been provided for you.

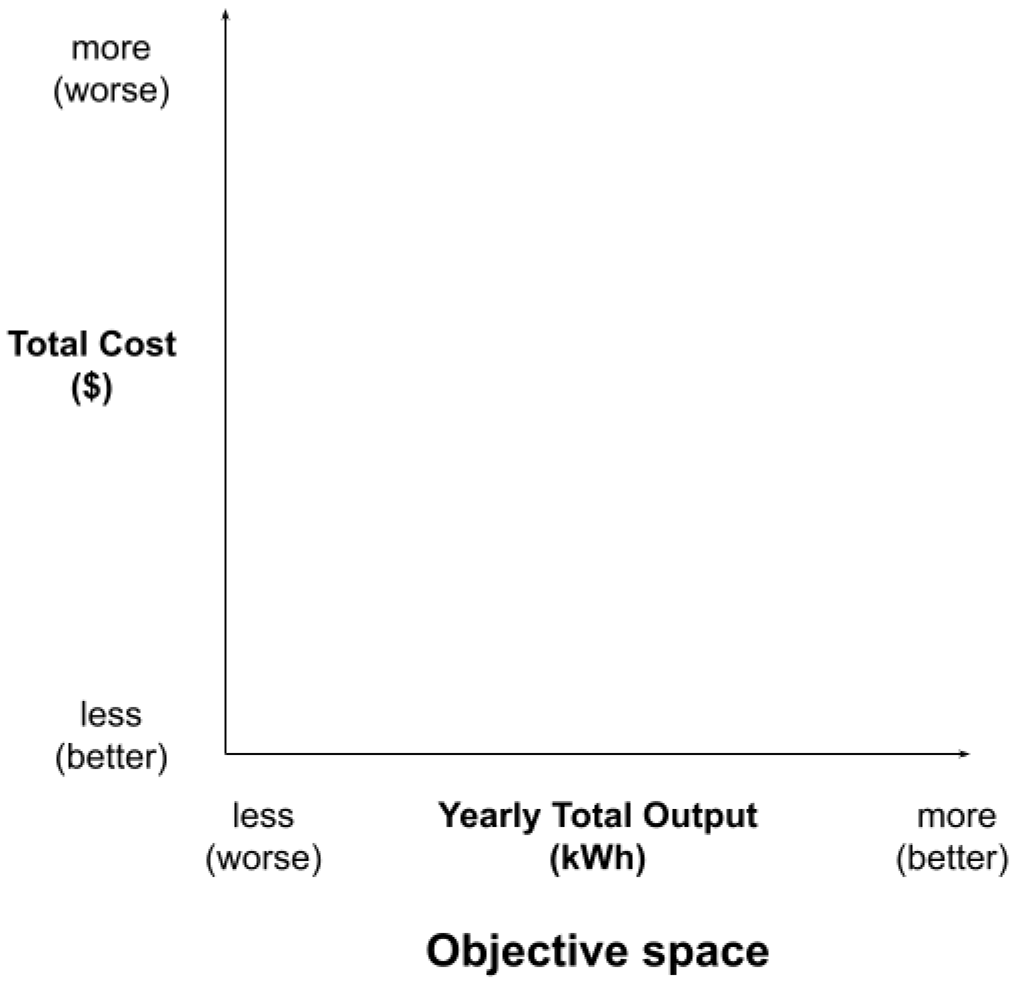


Design space

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 that you have decided that material and spoke width are two important variables of your car wheel design. So, how do you decide whether to 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 potential design solutions 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 wide spoke width to more equally distribute pressure 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.

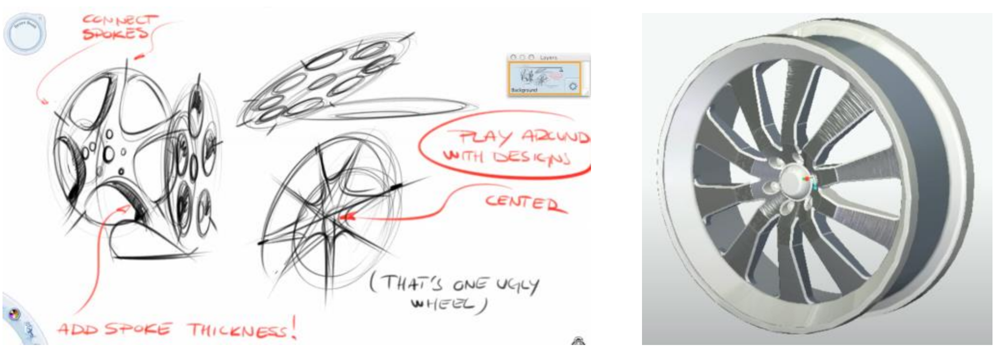
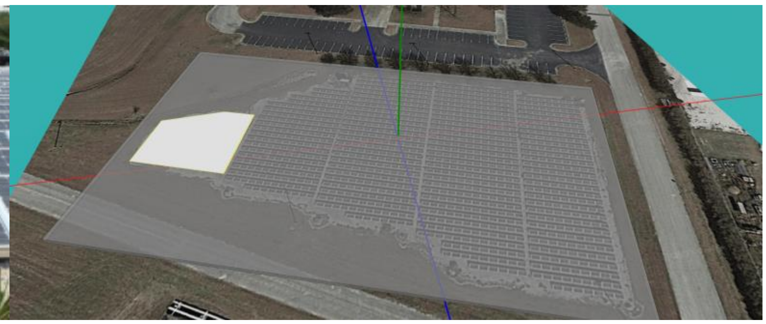


Figure 4. *Exploration in car wheel design.* ***Left,*** *Designers often start by sketching various concepts and ideas. They explore different shapes, patterns, and textures that may enhance the performance or aesthetics of the wheels.* ***Right,*** *Designers translate their conceptual sketches into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

Practice example: Solar farm design

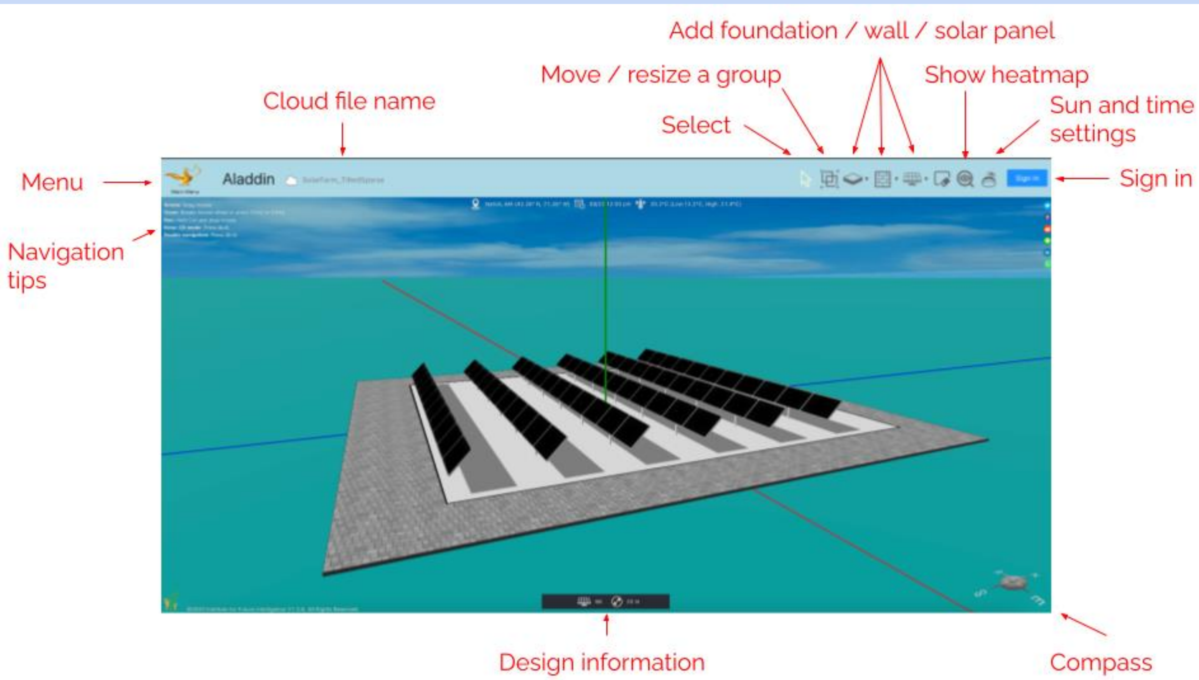
Previously, you gained some initial understanding of the definition of the solar farm design problem by looking at its design space and objective space. This next practice example will help you explore the design space in a more realistic context.

Imagine 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.**

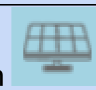
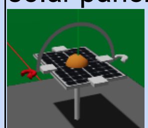
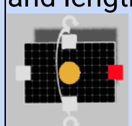
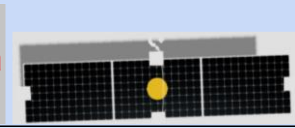


Click here to open the *Aladdin* model of the Pickle solar farm. Make sure to Sign in to your account, so your design can be saved.

***Aladdin*: Quick Start**

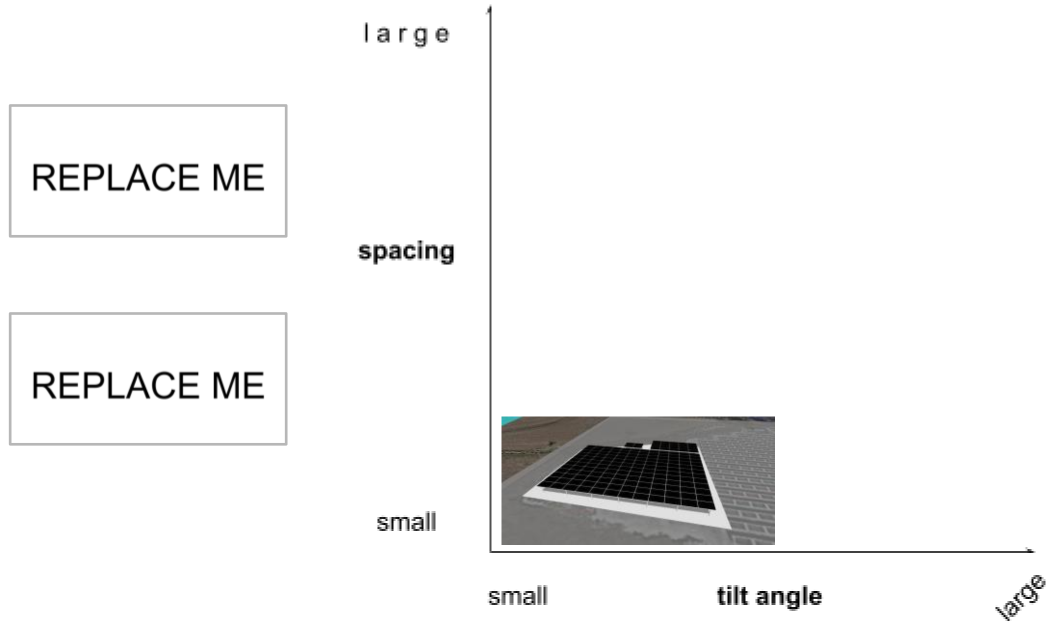


When you open the *Aladdin* model, you can:

Add new solar panel	Click on  icon
Move solar panels	Drag the orange center of the solar panel 
Rotate solar panels	Click and drag the curved arrows next to the solar panel  OR right click on the solar panel and select "Relative Azimuth"
Change solar panel tilt angle	Drag along the arch above a solar panel  OR right click on solar panel and select "Tilt Angle" to set a precise value
Expand solar panel	Click and drag the white dots on any side of the solar panel to expand the solar panel row width and length  
Copy and paste new panels	Right click a solar panel and click "copy" then select another area on the solar farm and right click and click "paste"
See coordinates of solar panel	Hover over solar panel to see coordinates 

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*. Once you are done:

- **Take a screenshot** ("Main Menu > File > Take Screenshot")
- **Replace the first image placeholder below** (Right click > "Change Picture" > 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.

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 choose between competing options?

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.** The remaining non-dominated designs form the Pareto Front. In the car wheel design example, the Pareto Front will include one design optimized for durability, one design optimized for safety, one design optimized for comfort, one design optimized for aesthetics, and so on for each specified design objective.

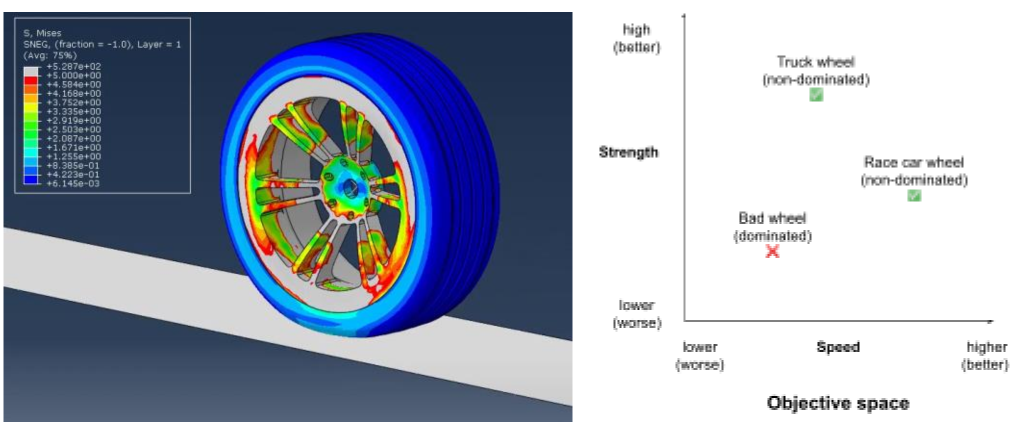
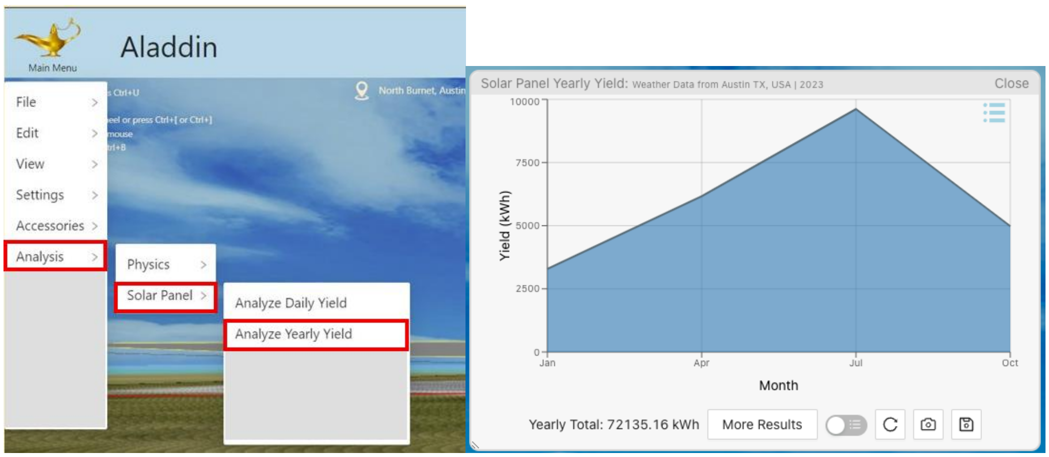


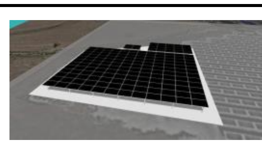
Figure 5. *(a) Evaluation of a car wheel design using computer-aided engineering (CAE) software. (b) A comparison of three car wheel designs in the objective space.*

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.**

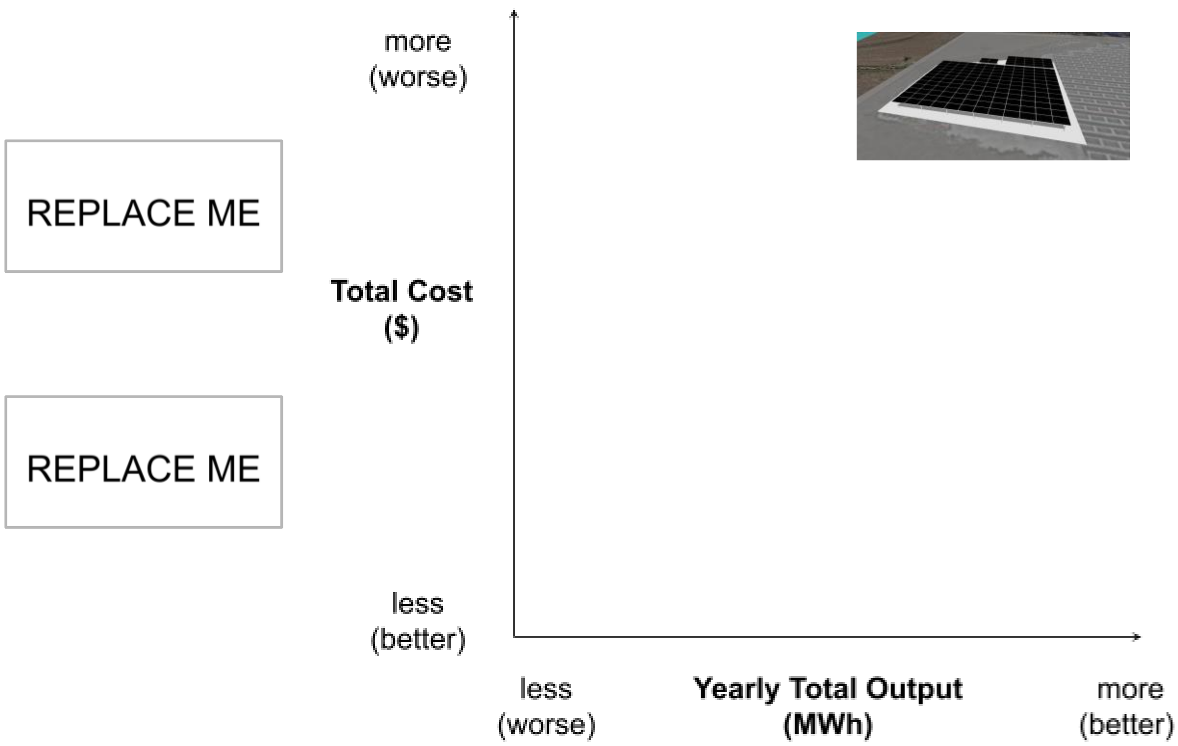
Practice example: Solar farm design

3. Take this chance to evaluate the two solar farm designs you generated earlier. Analyze each design by clicking ‘Main Menu’> ‘Analysis’> ‘Solar Panel’> ‘Analyze Yearly Yield’ and **record the results in the table below.** Click ‘More Results’ on the graph to show all of the results.



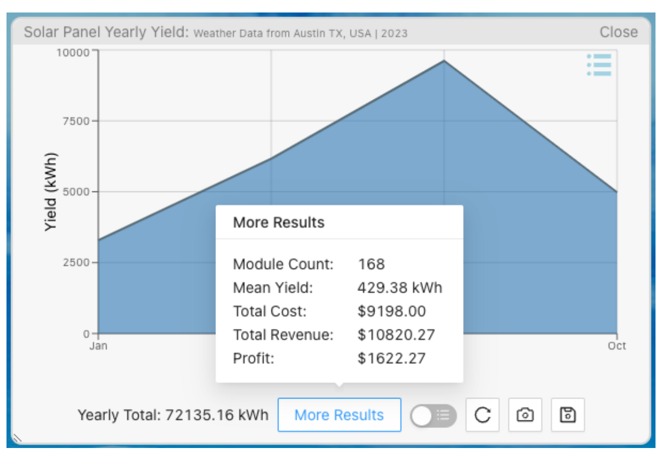
	Design 1	Design 2	Design 3
Variable: Tilt angle	small	large	*[Insert your own design choices]*
Variable: Spacing	small	large	*[Insert your own design choices]*
Screenshot			
Objective: Yearly total output (kWh)	72135.16		
Objective: Yearly average output (kWh)	429.38		
Objective: Total cost ($)	9198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

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



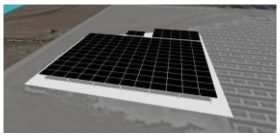
Objective space

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:



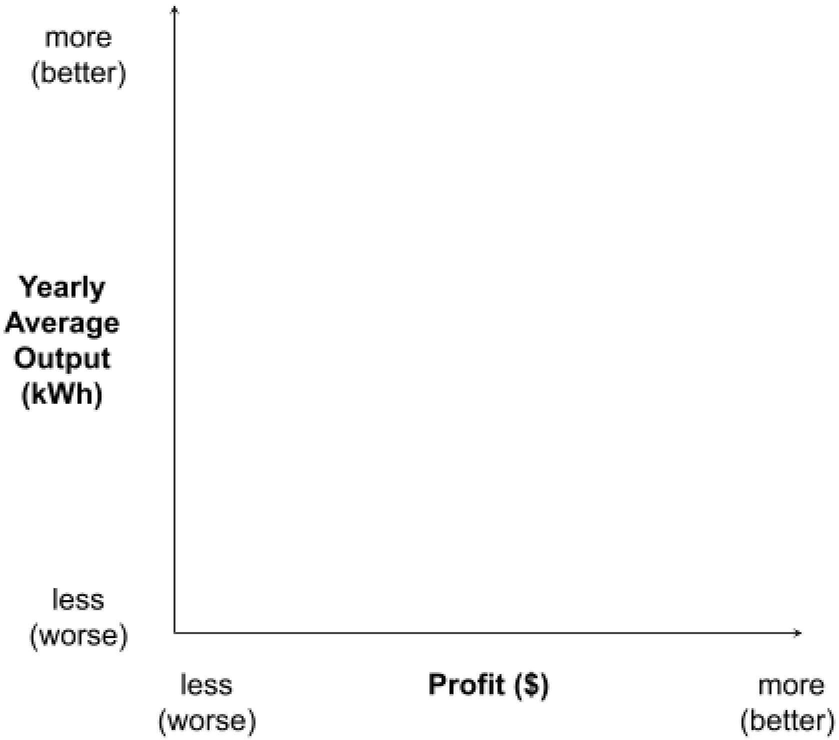
- **Yearly Profit** = Total Revenue - Total Cost
- **Yearly Average Output (or Mean Yield)** = Yearly Total Output / Module Count

5. 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.



REPLACE ME

REPLACE ME



A different objective space

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

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

8. 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). This can be achieved in several manners. For example, a designer can evaluate the strengths and weaknesses of different ideas by optimizing alternative concepts and comparing them against each other. This builds a deeper understanding of the design space and the objective space for the designer to consider as they work to refine **dominated designs** into **non-dominated designs** by modifying variables based on previous evaluation.

The goal of **Iteration** is to move from a dominated design towards a non-dominated design by modifying one or more variables. Ideally, each successive design should improve on the performance of the previous design, according to the specified objective.

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 changes when you use 7 spokes? 8 spokes?*

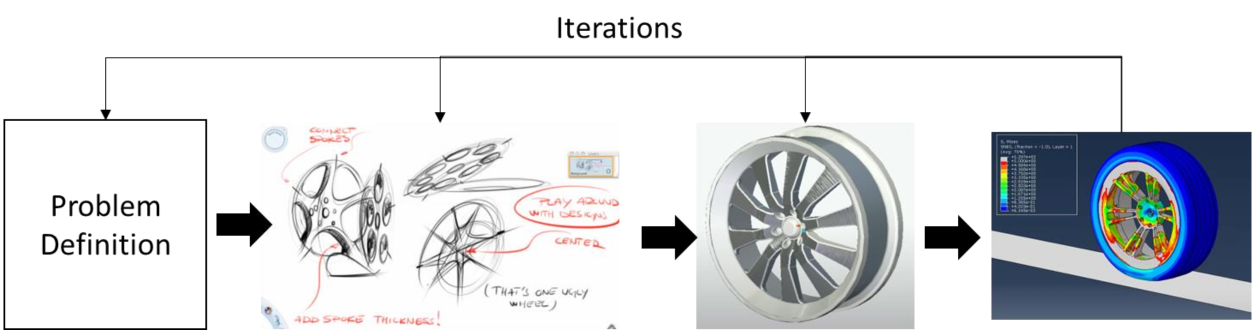
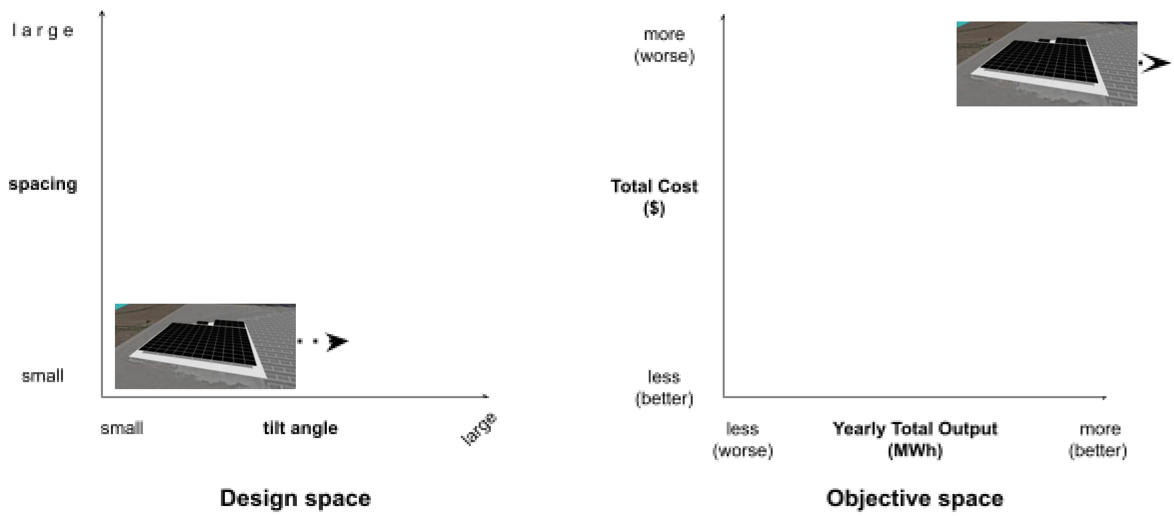


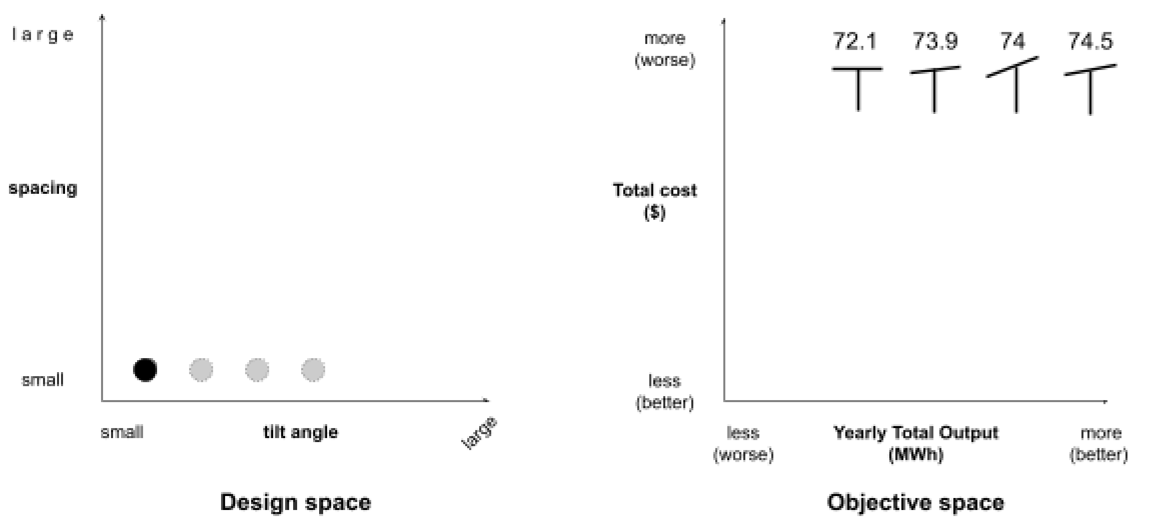
Figure 6. *Iteration in car wheel design. Through a series of iterations, designers cycle between the design exploration, evaluation, and (sometimes) the problem definition stages to continually refine and enhance the concepts until they reach the optimal design. The optimal design is the one that best 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.

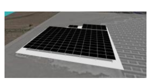


At this point, we can include such a design with both the original small spacing and an improved 20º tilt angle as one of the final design candidates.

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 expand solar panels
- Change the angle of solar panels
- Copy and paste solar panels

9. 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 18 into the green table below.
    - Save your best iteration as a cloud file.

	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]*
Screenshot (optional)						
Objective: Yearly total output (kWh)	72135.16			74474.07		
Objective: Yearly average output (kWh)	429.38			443.30		
Objective: Total cost ($)	9198			9198		
Objective: Profit ($)	1622.27			1973.11		

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

11. 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.)

Open-ended problem: Traditional Design

A southwestern University has announced that they plan to develop a solarized parking lot on campus. They have tasked you with proposing designs for this solarized parking lot using Traditional Design in Aladdin. [Click here to open the Aladdin design template](). The goal is to maximize profit and yearly average output.

Submit as many designs as you can. To leave spacing for utility vehicles, the University has requested a minimum of 7m Inter-Row Spacing, and a minimum of 3.5m Pole Height.

Use the design space graph below as a guide. Place your designs in the design space by inserting links or screenshots.

Yearly Average Output (kWh)				
>=500: Exceeds expectations	*[insert link here]*	*[insert link here]*	*[insert link here]*	*[insert link here]* *Aim at here!
>=475: Meets expectations	*[insert link here]*	*[insert link here]*	*[insert link here]*	*[insert link here]*
>450: Approaching expectations	*[insert link here]*	*[insert link here]*	*[insert link here]*	*[insert link here]*
<450: Not meeting expectations	*[insert link here]*	*[insert link here]*	*[insert link here]*	*[insert link here]*
	<2,900: Not meeting expectations	**>=2,900:** Approaching expectations	**>=3,100:** Meets expectations	**>=3,300:** Exceeds expectations

Profit ($)

Give a brief description of your design process and discuss the best design(s).