Lecture 1.5
Engineering Solutions through Product Design
How do Engineers Design Ingenious Inventions?

An engineer is a practical person who creates solutions to meet the needs of humanity. Sometimes, we need a product – a tool – that can aid us in our tasks.

For example, doctors need to diagnose ailments by examining what is inside the human body. But we don't want to cut up every patient just to achieve this goal. It's too messy! Enter the engineer who uses scientific principles to solve the problem. The result is a plethora of ingenious inventions like X-ray machines, scopes, CT scan machines, MRI (magnetic resonance imaging) machines, and more.

To demonstrate the questioning processes involved in designing products, I will use the example of the NUS Formula Race Car that I have been supervising for many years. Every year, I supervise a group of students who will build a race car from scratch and they will race in it at the annual Formula SAE international competition at the Michigan International Speedway, USA.

Each year we aspire to build a faster car than before. But we also have to ensure that the car is as safe as possible, especially since we have NUS students inside going at very high speeds.

There are many considerations and many questions involved in the design of products. Here, I'd like to introduce you to two conceptual tools that engineers use throughout the entire design process. They are: ***under-design*** and ***over-design***.

These conceptual tools are highly versatile, and we use them to question and evaluate whether the choices we make fulfill the specifications of our problem, and whether the design is both safe and reliable for the users.

Here, I'll just focus on one aspect of race car design so that I can walk you through these two conceptual tools. Let's begin!

From Newton's second law of motion, Force = Mass x Acceleration, we know that if we build a lighter car, it can accelerate faster. However, a lighter car will be flimsier, and parts of the car will break more easily, especially with the huge forces experienced by the car at high speeds.

How do we decide what materials to use for our car?

Obviously, we want to build the best possible car despite the constraints we encounter, whether it is a financial or physical constraint.

Let's start with selecting the materials for the car chassis. There are two aspects to consider. First, what materials are best suited for the chassis, and second, whether we can acquire the materials in the most cost-effective way. Let me take you through the thought process in choosing the right material. Let's imagine that we have to choose between aluminium, titanium, synthetic carbon fibre, and steel.

Aluminium does not corrode and it's a very light material, allowing cars to travel fast. But it is too soft and will flex under load, making the car rather unreliable, especially under high loads and in the event of a collision. We need to consider the safety of the driver and protect him by building a cabin strong enough to take such stresses. Aluminium cannot fulfill that requirement at all.

From an engineering perspective, a car built with aluminium would be under-designed, that is, it does not meet the needs, or the specifications, of the problem.

Titanium is very strong and very safe. It is light, and it does not corrode. While it would seem like the perfect material, from an engineering perspective, a car built with titanium would be over-designed, that is, it far surpasses the specifications of the problem. We don't need cars to be that strong, and especially not at that price. Titanium is far too expensive. Few can afford such a car, and the company will not be able to make a profit.

Synthetic carbon fibre composite is extremely light and strong, but very costly. This material will satisfy the specifications of high-end cars, for which there is an exclusive clientele, so the company could make a profit using this material.

For our purposes, this material is neither over- nor under-design. But as ideal as this material may be, cost may be a constraint preventing us from choosing this material. In which case, we'll need to look at other possibilities that may do a satisfactory though imperfect job. In other words, we have to make an educated choice on "the lesser of two evils." And we'll have to revise our original design to cater to the newly chosen material.

What about steel? Steel is readily available in large quantities and it is easy to fabricate by bolting or welding. The cost is also rather reasonable. It is strong and can protect the driver in the event of a collision. The downside is that it is heavy, and it corrodes easily. But because steel is quite affordable, we can still revise our original car design in order to rectify the weight and corrosion problems.

In this imaginary scenario, steel is the "lesser of two evils" solution that adequately meets the specifications of the problem. In fact, steel has been the workhorse for vehicle construction for over a century, and still is today.

Moving on. It's important to emphasise here that product design isn't just about designing a product that works. We, engineers, have a moral responsibility to ensure that our products are safe and reliable.

In 1994, Ayrton Senna, the F1 racing legend, was killed when his car ran into a wall during a Grand Prix. For this reason, the chassis of a present-day F1 car is deliberately built to be super-strong in order to assure safety for the driver in case of collision at high speeds.

To ensure that our car is safe, we need to identify the parts of the car that run the danger of breaking under additional stress. Those parts are under-designed and will need to be strengthened. But doing this will increase both the cost and weight of the car, as is the case of our NUS Formula Race Car.

We can reduce the cost and weight a little by identifying those parts of a car that can take more stress than others without breaking but do not affect the safety of the driver. These parts are over-designed, and we can reduce the amount of material to bring down both the cost and the weight.

Sometimes, it is not possible to predict the actual performance of the car until we monitor its performance on the race track. The observations collected during test runs and competitions are crucial for improving the car's performance. Every time a component breaks, there are a myriad questions that arise, such as: (1) was it caused by a sudden bump on the road which we did not anticipate? (2) Was the failed part under-designed? (3) Was it caused by the driver changing gear at the wrong time?

In order to diagnose the problem, we record massive amounts of data on a computer during each test run. We can always check whether there are any anomalies in the forces acting on the damaged component. We also have a soft copy of all the design drawings for every component of our car as well as the computer simulation data, which we can re-visit every time we suspect the component has been under-designed.

And believe it or not, we do keep data of every gear change made by the driver, down to millisecond accuracy. All these allow our student engineers to diagnose what was the real cause of the failure. Without these data, we would need to rely on sheer guess-work, which is the antithesis of engineering.

As we have limited time to consider all the possibilities of failure, we need to choose which are the more likely causes based on our basic engineering knowledge and previous experience.

Product design is an iterative cycle of repeated refinements. We don't just want a product that solves a problem. We want it to solve the problem in a safe and reliable manner. In this way, engineers are able to create ingenious inventions that makes life better for all of us.