Lecture 1.4
Monitoring and Evaluation
How do Engineers Discover Flaws in their Understanding and Solutions?

Apart from modelling, the second component engineers usually engage in is monitoring. Monitoring may involve sensors, or taking samples back to a lab. It is a very versatile process that engineers use in all stages of the problem-solving process: it provides us with information essential for setting up, calibrating and verifying our models, it helps us to discover flaws in our understanding of a problem and the solutions we create, and more importantly, monitoring keeps us grounded to reality: it allows us to check on the actual performance of the things we create and provide corrective measures, where necessary. It is an important tool that gives engineers the much-needed checks and balances to the work we do.

As an Environmental engineer, I'll use the example of what we do in an Environmental Impact Assessment, or EIA, to take you through the questioning processes involved in monitoring. We conduct EIAs before any major construction project which might potentially harm the environment. This allows us to protect the environment and its living resources.

Let me take you through the process!

Let's imagine that we'll need to build a wastewater treatment plant. This treatment plant will discharge treated wastewater, or effluent, into a nearby lake.

How clean should the effluent be? The more sophisticated the treatment, the cleaner the discharged effluent will be, and the environment will be better protected. But this also means that the cost of wastewater treatment will be greater. In some cases, we might not be able to go for the cleanest option possible. Every field in engineering will have some quality and safety guidelines and standards, which are determined both scientifically and from past engineering experiences.

For our example here, these standards prescribe how contaminants should be kept below certain concentrations, beyond which they become harmful or toxic. We can decide on the concentration levels to use, based on the overall objective of who or what we are trying to protect. If it's a lake where humans swim in, you'd want the water to be clean enough so you won't fall sick by accidentally swallowing the water. Hence, the standards will be much stricter than if the water was just used for boating or non-contact activities.

To design the best wastewater treatment to meet our objectives, engineers will have to use models to compute the best parameters for the design.

But before we create a model, we first need to monitor the conditions of the lake. This will give us what's known as the ***baseline conditions***.

Baseline conditions are essential for two reasons: (1) First, it gives us an understanding of the lake's conditions before we implement anything. This is important as it will allow us to set achievable and realistic objectives and targets. For example, if the lake is already very polluted, treating wastewater to high levels of purity would not only be very costly but it wouldn't do much to improve the lake's condition. Perhaps, we should clean up the lake first!

(2) Second, the baseline conditions will give us a point of reference for assessing any change in the future. It provides the basis for simulating future predictions, e.g. pollution levels will increase steadily from baseline levels, at a certain percentage over the next 10 years. And it allows us to assess the efficacy of various treatment solutions, whether simulated or implemented in real life.

As we have learnt in the previous video, engineers create models – abstract and simplified representations of actual conditions of a system – so that we can test various scenarios and predictions. Baseline conditions provide us with the much-needed data to do just that.

How do we know that the baseline conditions are correct, or representative of the lake? We might have taken a reading on a very bad day. This is where we'll need to ensure that the frequency and period of monitoring, as well as the areas chosen, are sufficient to ensure a representative coverage of the lake.

Let's imagine that we have now created a model of the lake. This will now allow us to predict the concentrations of contaminants in the water based on the effects of different treatment processes.

Underlying all models are assumptions about a system. This is what allows us to simplify real world conditions into a model that we use.

But how do we know if we have made the right assumptions? How do we know whether the model is accurate?

We won't know for sure until we check it against the data we've gathered. We do this by comparing the model output with actual field data. Here, monitoring is used for two purposes: ***calibration*** and ***verification***.

If the model output and field data match closely, we know our model is working properly. However, if our results are very far off, then it may mean that there is something wrong with our original assumptions. For example, we might have assumed a linear relationship between two variables, when they were in fact non-linear. Or we may have neglected certain external factors, like migrating birds that contaminate the lake's purity at certain points in the year. We may need to revise our assumptions behind the model.

However, most of the time, the results are usually off, but not by a lot. And we may have to 'tune' our model to get the best fit. This is done by adjusting the coefficients of the variables in the model within reasonable ranges, so that the model output matches the measured data that we've collected from monitoring as best as possible. This is called ***calibration***.

How do we know if the model is correct or good enough? We will have to test it against a second independent set of data. This process is known as ***verification***.

Moving on. Let's assume that our model is a good one. We have validated, calibrated and verified it for accuracy, and it generates the required output that meets the objective, i.e. it allows us to determine the best wastewater treatment design. This means that we can proceed to the next step!

We can now build the wastewater treatment plant. But this is not the end of the story. We need to make sure that the wastewater treatment plant does what it is meant to do and that it satisfies our objectives.

Again, we'll need to resort to monitoring to ensure that the measurements of contaminants in the lake do not exceed the water quality standards for the lake's intended use. If, for example, we detect that the concentration of contaminants has gone above the safe level, then we will need to implement ***engineering controls***. These are measures built into the plant, equipment, or process, in order to correct deviations from the required output. For example, we could increase the level of treatment in the plant to remove specific wastewater contaminants that are problematic.

This is an iterative process. Engineers will have to refine the controls from time to time. In some cases, monitoring may tell us that our circumstances have changed so much that we will need to revise our original model. This may be due to unforeseen circumstances such as climate change or a permanent increase in pollution due to a new industrial development nearby. Engineers may have to modify the model and the processes until the concentration of contaminants complies with the required water quality standards.

I'm sure some of you may be asking: How often should I be monitoring? How many sampling points do I need? Where should I be monitoring? How confident am I of the data? These are very important questions! In practice, we can't really monitor everything and everywhere all the time. We are constrained by resources, cost and possibly, the sensor technology itself.

In the example of wastewater discharge, given the limited resources at our disposable, we will need to limit our monitoring to certain strategic parts of the lake. For example, which are the likely places that might be problematic? An area where people like to swim? How can we space out the sampling points to cover as large an area as possible, and in a way that's representative of the entire lake? What about the seasonal variation in lake parameters? And the effects of monsoon rains? Should we go for a bimonthly or monthly sampling to cover this variation?

Thus far, I've been talking about how monitoring provides engineers with the much-needed audits. But who audits the auditor? How do we assess whether the monitors are working well or that our measurements are reliable? It's easy to detect a broken sensor as there's no reading coming out from it. But it's much harder to detect a defective sensor (or a sensor blocked by debris) that's giving us incorrect data.

There are various strategies. Here, I will just mention two. If it involves sensors, we can do something like a quality check by calibrating the sensors against calibration standards with known outputs. If it involves sending samples to a lab for example, we can compare the results with a third party.

How do we assess the effectiveness of the monitoring strategy? Basically, we have to go back to the overall objectives of our system. Are we providing sufficient protection to the public and the aquatic ecosystem? Does our monitoring strategy supply us with enough data to make informed decisions as to whether we should implement control measures or not? At the end of the day, the monitoring effort should be in line with the goal of maintaining public safety and ecosystem health.

As you can see, monitoring is an invaluable instrument that accompanies the engineer every step of the way in the problem-solving process. Monitoring keeps us firmly grounded to reality, and it helps us to discover our blind spots and false assumptions, and it helps us discover things we might not have known previously.