FOOD SCIENCE AND TECHNOLOGY

Lecture54

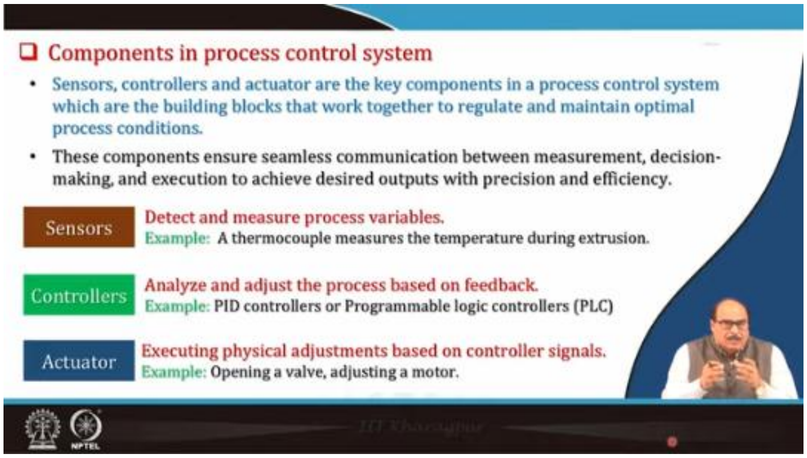
Lecture 54: Process Control and Automation

Hello everyone, Namaste.

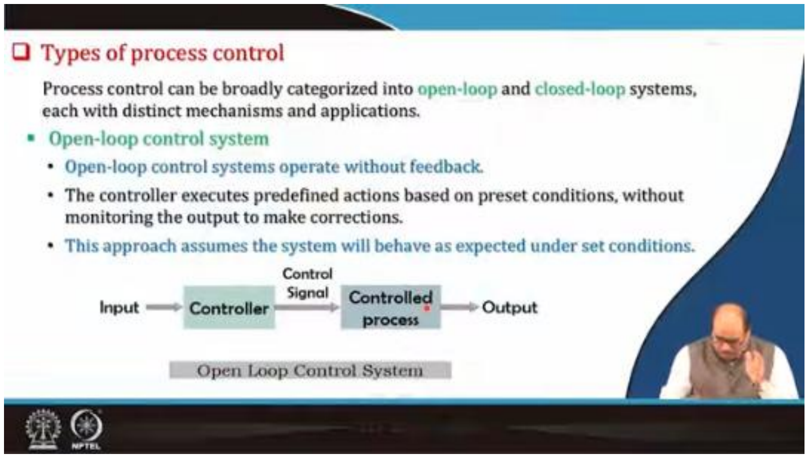
In today's class, that is lecture 54, we will discuss process control and automation with reference to the food industry.

We will discuss what various process control systems are used in the food processing industry, components of process control systems. Process control in food manufacturing, process control strategies, and we will also discuss, towards the end, automation in food manufacturing.

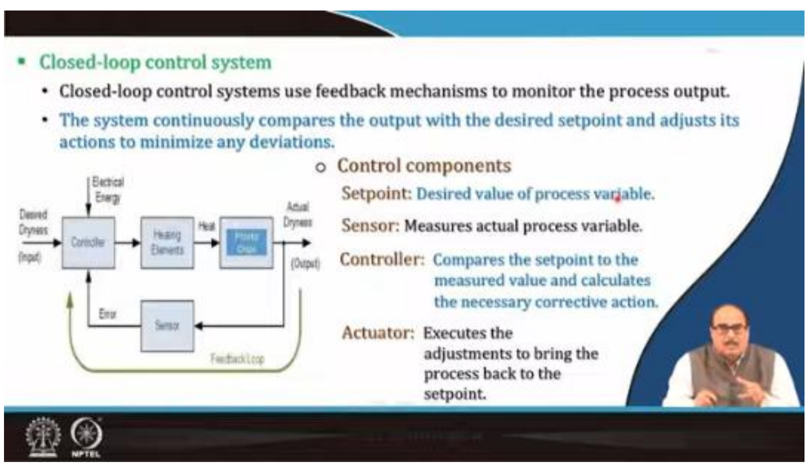
So, what is a process control system? A process control system is an integrated framework that monitors and regulates the production parameters to ensure the safety, quality, and efficiency of food products. The process control system has been applied in various food industries like pasteurization control in dairy processing, fermentation monitoring in beverage production, canning operations in preserved foods, and baking processes in bread manufacturing in the bakery industry.



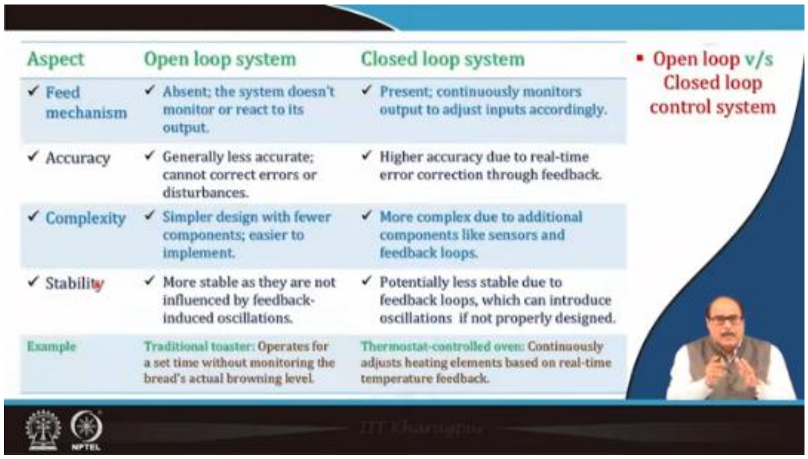
So, the components of a process control system include sensors, controllers, and actuators. That is, sensors, controllers, and actuators are the key components in a process control system, which are the building blocks that work together to regulate and maintain optimum process conditions. These components ensure seamless communication between measurements. Decision making and execution to achieve the desired output with precision and efficiency. For example, sensors detect and measure process variables. A thermocouple measures the temperature during the extrusion process or many other food processes. Similarly, controllers analyze and adjust the process based on feedback. For example, a PID controller or a programmable logic controller. They analyse the data and adjust the process variables based on the feedback, etc. Then, actuators execute physical adjustments based on the controller signals, like opening a valve, adjusting a motor, and so on.



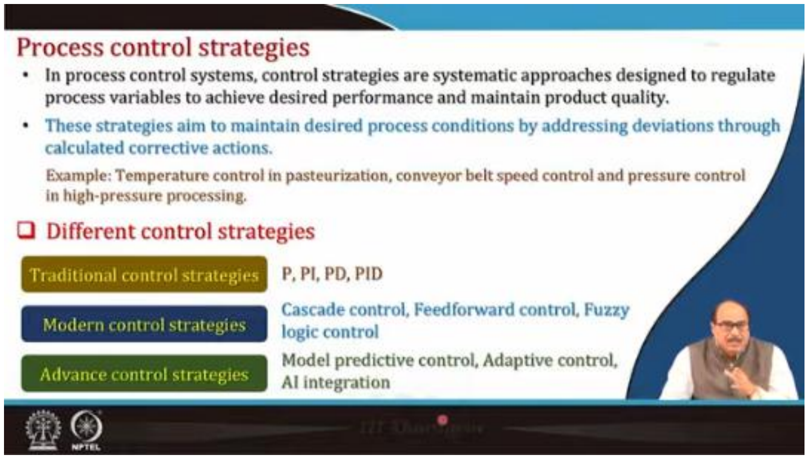
Let us briefly discuss what the different types of process controls or process control systems are. That is, process control can be broadly categorized into open-loop and closed-loop control systems, each with distinct mechanisms and applications. Open-loop control systems operate without any feedback; the controller, as you can see in this line diagram. The controller executes predefined actions based on preset conditions without monitoring the output to make corrections. This approach assumes the system will behave as expected under set conditions. So, that is the open-loop control system.



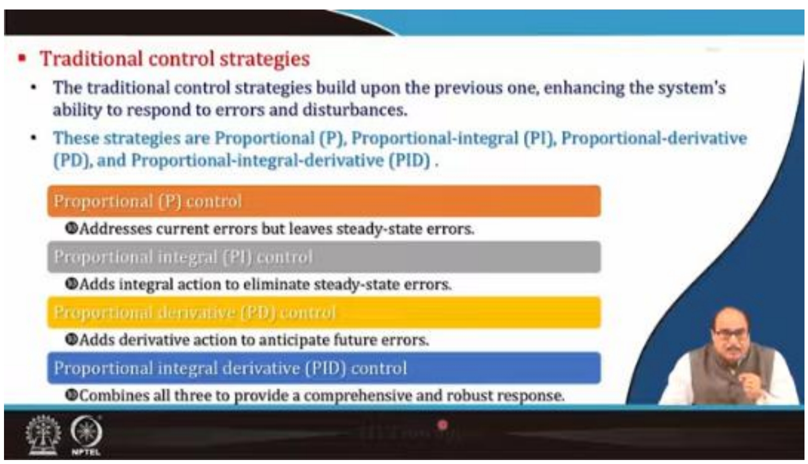
Whereas the closed-loop control uses a feedback mechanism to monitor the process output. The system continuously compares the output with the desired set point and adjusts its actions to minimise any deviations from the desired set point. For example, the various components of the closed-loop system are the set point, which is a desired value of process variables. Sensors measure the actual process variables, and the controller compares the set point to the measured value and calculates the necessary corrective actions, whatever is needed. And then finally, it sends, and like you can see, there is feedback alright after it gives that. And then the actuator executes the adjustment to bring the process back to the set point. After the feedback, if there is any error, then the actuator will work and bring the value to the set point and give the desired output.



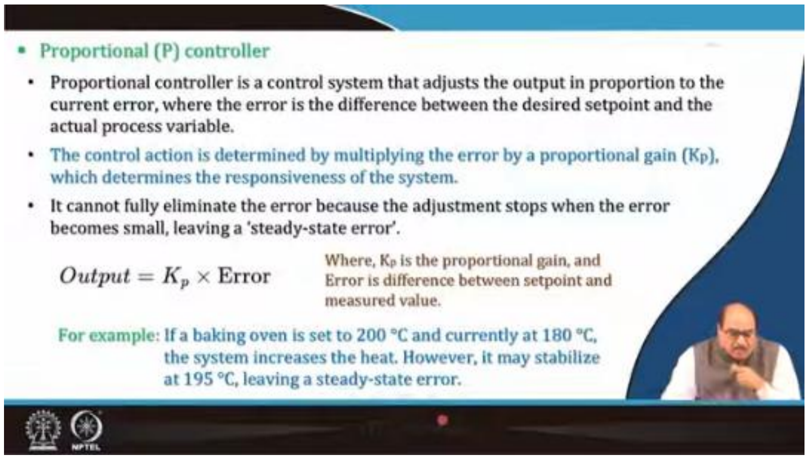
Then, if you have a comparison between an open-loop control system and a closed-loop control system. So, first thing, the feed mechanism is not definite; it is absent in an open-loop control system, the system does not monitor or react to its output. Whereas a closed-loop control system has a definite feed mechanism, it continuously monitors output to adjust inputs accordingly. Open-loop systems are generally less accurate. They cannot correct errors or disturbances, whereas closed-loop systems are more accurate. They have high accuracy due to real-time error correction through feedback. Open-loop systems have simpler designs with fewer components; they are easier to implement. Whereas, the closed-loop systems have more complex designs due to additional components like sensors and feedback loops, etc. The open-loop systems are more stable as they are not influenced by feedback-induced oscillations. Closed-loop systems are potentially less stable due to feedback loops, which can introduce oscillations if not properly designed. If you look at an example of the open loop system, it may be the case in traditional toasters, which operate for a set time without monitoring the bread's actual browning level. In the closed-loop system, if you have a thermo-resistant control oven, then it continuously adjusts heating elements based on real-time temperature feedback, and accordingly, it gives a comparatively better-quality output.



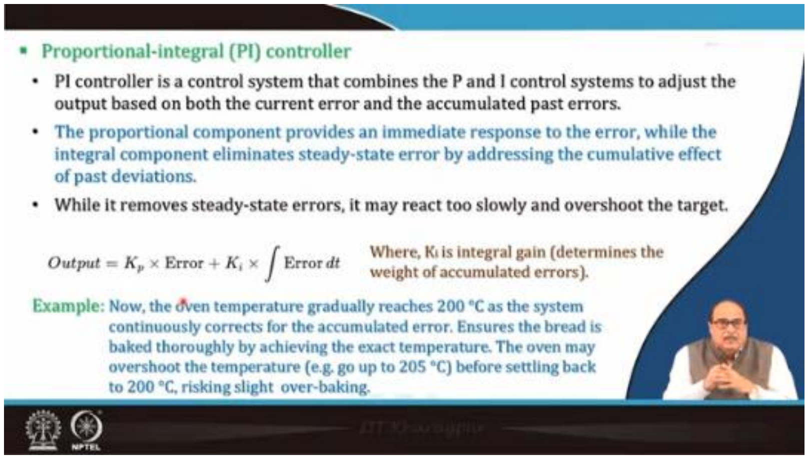
Then, process control strategies, in the process control system, are systematic approaches which are designed to regulate process variables to achieve desired performance and maintain product quality. These strategies aim to maintain desired process conditions by addressing deviations through calculated corrective actions. For example, if you see the temperature control in pasteurisation, even conveyor belt speed in food handling systems or pressure control systems in high-pressure processing, etc. There are traditional control strategies like P, PI, PD, PID or modern control strategies like cascade control, feed forward control, fuzzy logic control or advanced control strategies that is which include modern predictive control, adaptive control, and artificial intelligence integration with the control system.



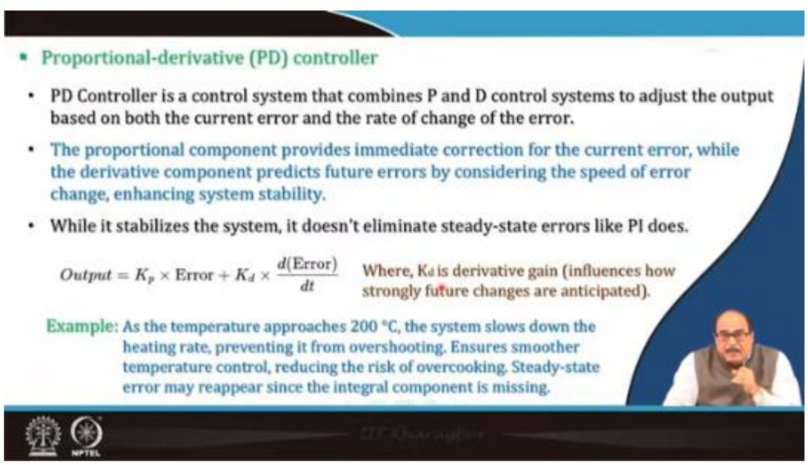
So, let us briefly discuss the little details of these traditional control strategies, like traditional control strategies which build upon the. The previous one, enhancing the system's ability to respond to errors and disturbances. These strategies include a proportional control system, a proportional integral control system, which is commonly known as PI, a proportional derivative control system or a proportional integral derivative control system, which is commonly known as PID. This proportional control addresses current errors, but leaves the steady-state errors. Proportional-integral control adds integral action to eliminate steady-state errors. Proportional derivative control adds a derivative action to anticipate future errors, whereas the proportional integral derivative control combines all three. to a comprehensive to provide a comprehensive and robust response.



So, the proportional control is a system that adjusts the control output in proportion to the current error. The error is the difference between the desired set point and the actual process variable. The control action is determined by is output is determined by multiplying the error by a proportional gain, K_p, which determines the responsiveness of the system. $Output = K_p \times error$, where K_p is the proportional gain and error is the difference between the set point and the measured value. So, this cannot fully eliminate the proportional controller's inability to fully eliminate the error between the adjustment stops when the error becomes small, leaving a steady-state error. In the bakery industry, a baking oven—let us say that the baking oven is set to 200°C—and currently, it is at 180°C. So, that system increases the heat. However, it may stabilise at 195° C; it may not actually reach 200° C, leaving a steady-state error.



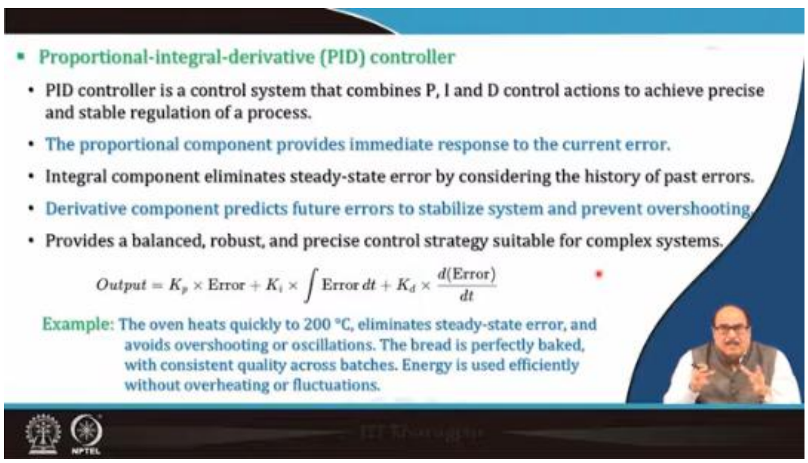
While it removes steady-state errors, it may react too slowly and overshoot the target. $Output = K_p \times error + K_i \int error\ dt$, where K_i is the integral gain that determines the weight of the accumulated errors. So, if we take a similar example of the baking oven, the oven temperature gradually reaches 200 °C as the system continuously corrects for the accumulated error. It ensures the bread is baked thoroughly by achieving the exact temperature if the proportional integral PI controller is used. The PI controller in this case will ensure that the bread is baked thoroughly by achieving the exact temperature. And the oven may, however, overshoot the temperature because it may even happen that it may go up to above 200, like 205° C, before setting back to 200. And this may have little risk of overbaking, slight overbaking is fine.



This can be further controlled in the PD controller, which is a proportional derivative controller. It is a system that combines proportional and derivative control systems to adjust the output based on both the current errors and the rate of change of the error. The output, which was in the earlier PI, may go up to 200 degrees, 205 degrees Celsius, that is, control here. The proportional component provides immediate corrections for the current error, while the derivative component predicts future errors by considering the speed of error change, enhancing the system's ability. While it stabilizes the system, it does not eliminate, however, the steady state errors like the PI does. So, here

$$Output = K_p \times Error + K_d \times \frac{d(Error)}{dt},$$

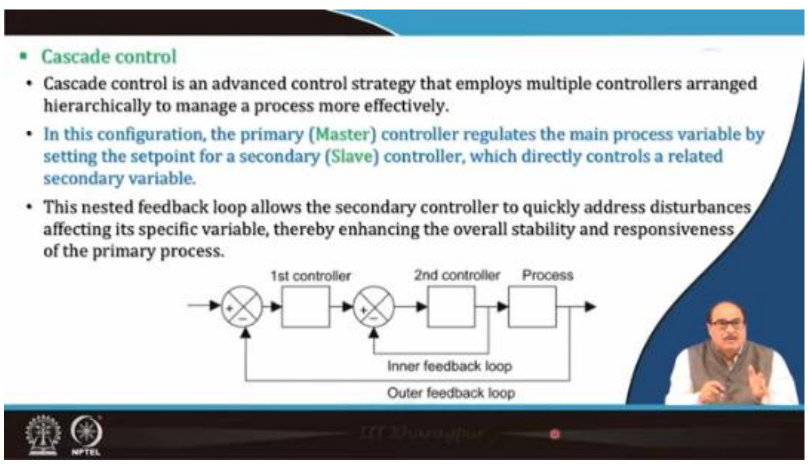
that is, the rate at which the error occurs. K_d is the derivative gain, which influences how strongly future changes are anticipated. So, in the same example, if you see that here, 200 degrees Celsius, the temperature as it approaches the system slows down. The heating rate is controlled when the PD controller is there, and it prevents it from overshooting. It ensures smoother temperature control, reducing the risk of overcooking or overbaking. Our steady-state errors, however, may appear since the integral component is missing here; it is only P and D.



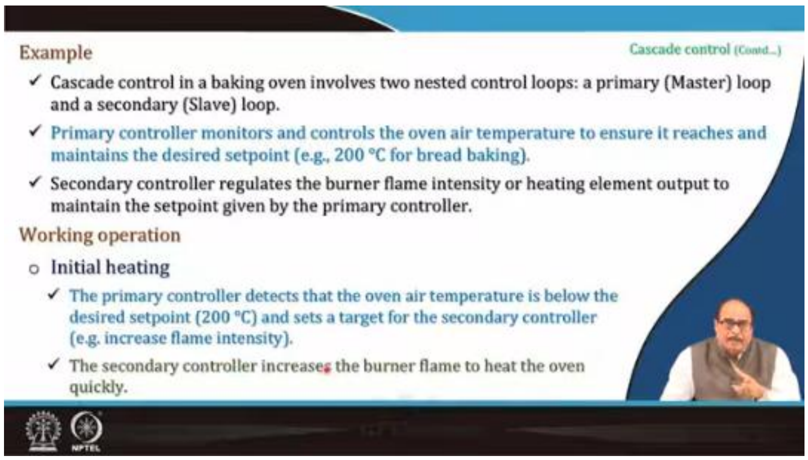
So, that is all when it is combined like P, I, D—when proportional, integral, and derivative. All three actions are provided in one unit, and they achieve precise and stable regulation of a process. And in this, all three components do their own job: the proportional component provides an immediate response to the current error. The integral component eliminates steady-state error by considering the history of the past. The derivative component predicts future error to stabilize the system and prevent overshooting. And all three together provide a balanced, robust, and precise control strategy, which may even be suitable for complex systems. So, the output here, you can say $Output = K_p \times Error + K_i \int Error\, dt + K_d \times \frac{d(Error)}{dt}$

So, all three of these are taken care of here. So, the same example—if you see here in the oven—when there is a PID controller, in that case, the oven heats quickly to 200 degrees Celsius, eliminates steady-state error, and avoids overshooting or oscillations. The bread is perfectly baked with consistent quality across batches, and energy is used efficiently without overheating or any fluctuations.

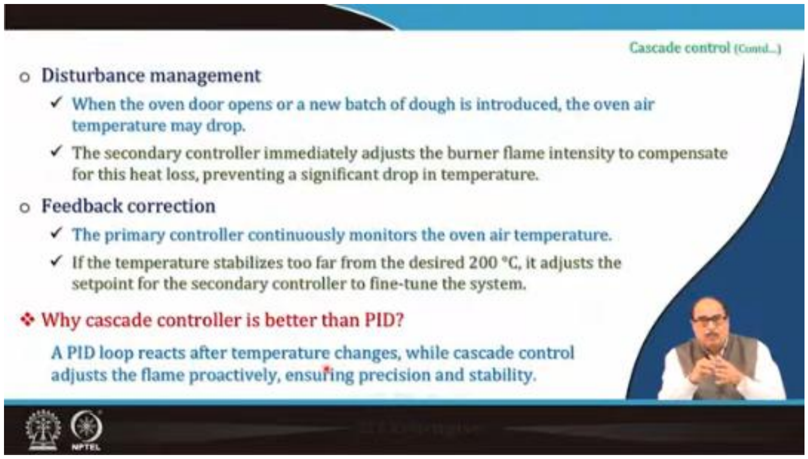
Then, let us talk about modern control strategies. They refer to advanced methods used to regulate complex processes by addressing the limitations of the traditional controllers like P, PI, PD, PID, etc., that we discussed a little earlier. So, these strategies incorporate sophisticated algorithms and predictive models to improve system accuracy, adaptability and efficiency. Modern approaches are particularly effective in handling multivariable systems. non-linear systems as well as external disturbances, if there are any, that are also taken care of by these modern controllers. So, as told earlier, the modern control systems may be cascading control, feed forward control and fuzzy logic controller.



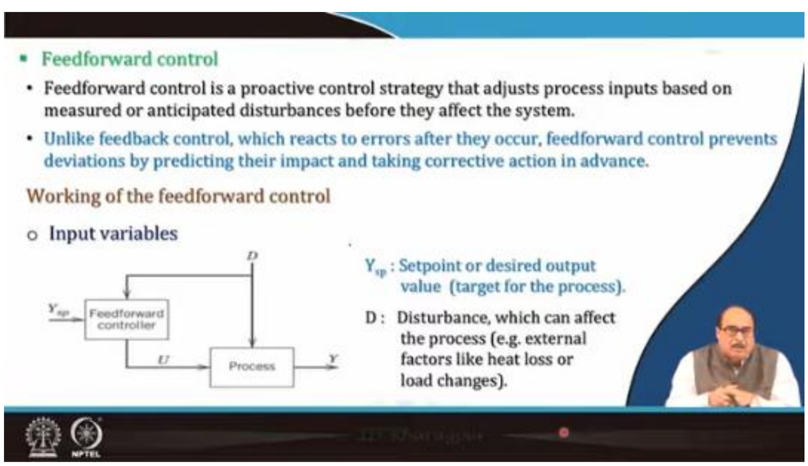
So, let us talk about the cascade control. It is an advanced control strategy that implies multiple controllers arranged hierarchically to manage a process more effectively, and as you can see here, there are two controllers, and they are going. So, in this configuration, there is a primary controller, which is also called a master controller, that regulates the main process variable by setting the set point. For a secondary controller, a secondary controller is generally called a slave controller and it controls a related secondary variable. So, this nested feedback loop allows the secondary controller to quickly address disturbances. Intern inner feedback loop or outer feedback loop, and if there are any variables or disturbances affecting a specific variable, these are taken care of by the slave controller or secondary controller, thereby enhancing the overall stability and responsiveness of the primary system.



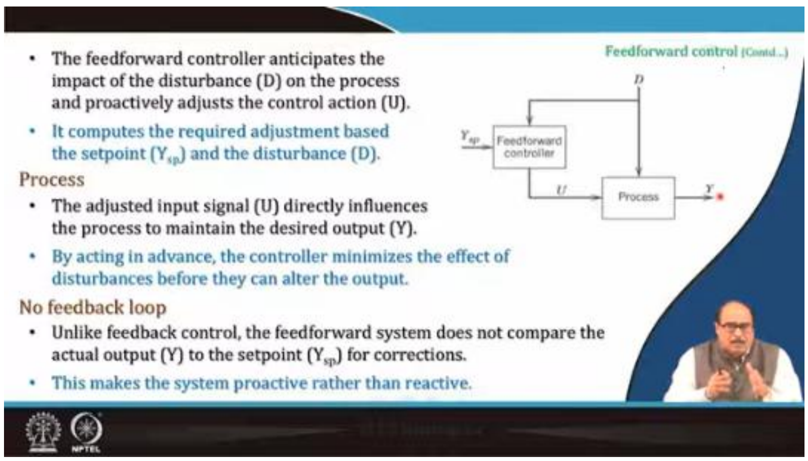
If we take the example of a cascade controller in a baking oven. involves two nested control loops like master loop as well as secondary controller slab loop and primary controller monitors the and control the oven air temperature to ensure it reaches and maintain the desired set point that what we discussed earlier 200°C for example, for breaking and the secondary controller in this case will regulate the burner flame intensity or heating element output to maintain the set point given by the primary controller. The primary controller gives a set point of 200 °C; the secondary controllers accordingly regulate the heating system to maintain 200°C continuously throughout the process. So, how it operates there is obviously, there is initial heating like the primary controller detects. that the oven air temperature is below the desired set point and sets a target for the secondary controller, such as what the target is given to the secondary control by the primary controller to increase the flame intensity. So, the secondary controller then increases the burner flame to heat the oven quickly.



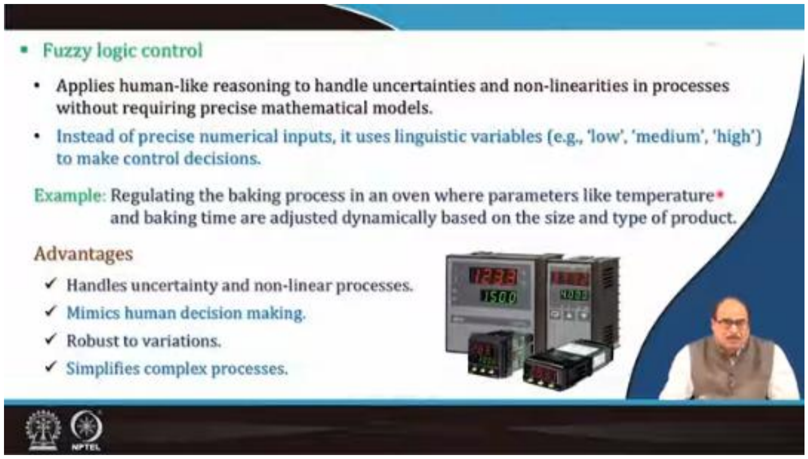
Then there is disturbance management, like when the oven doors are open for a time or for putting in a new batch of dough inside the oven, then in that case, the oven temperature may drop. So, the secondary controller in that case comes into action and immediately adjusts the burner flame intensity to compensate for the temperature changes inside the oven because of the opening and another thing. Therefore, it prevents a significant drop in temperature and maintains the quality and other operational efficiencies, energy, etcetera. And then, finally, there is a feedback correction. The primary controller continuously monitors the oven air temperature and the temperature. If the temperature stabilizes too far from the desired 200 °C, then it will adjust the set point for the secondary controller to fine-tune the system. So, that is the input disturbance and feedback corrections. That is how it works. And if you talk about why a cascade controller is better than the PID, meaning, it is a PID loop that reacts to temperature changes, while a cascade controller adjusts the flame proactively, ensuring precision and stability. It makes precise control of the temperature or whatever parameter you have at the set point, and then maintains and stabilises it precisely.



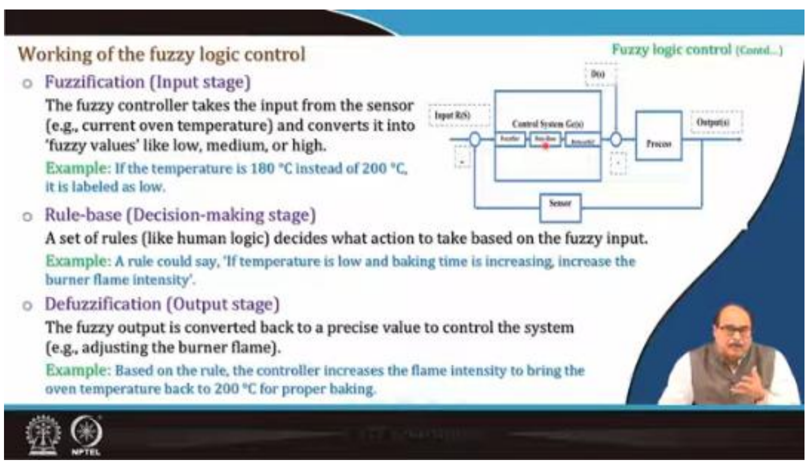
Then, another is the feedforward control. Feedforward control is a proactive control strategy that adjusts process inputs based on measured or anticipated disturbances before they affect the system. Unlike feedback control, which reacts to errors after they occur, feedforward control prevents deviations by predicting their impact and taking corrective actions in advance. And working—if you look at the feedforward control, suppose there is a feedforward controller and a set point Y_{sp}. The set points are the desired output values. And then there may be disturbances. D is the disturbance, which can affect the process, like external factors such as heat loss or load changes, etcetera.



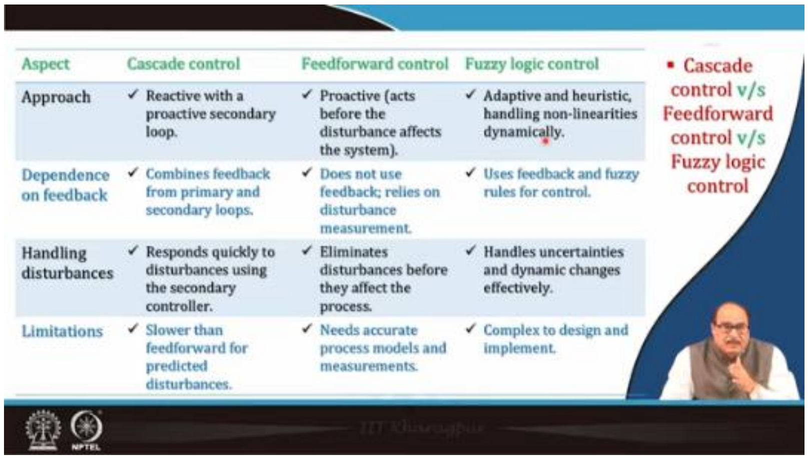
So, the feed-forward controller can anticipate the impact of disturbances on the process and proactively adjust the control actions. The computer computes the desired adjustment based on the set point Y_{sp}. and the disturbances D. So, taking into account both, it uses the set points and gives the desired output. The adjusted input signal directly influences the process to maintain the desired output, and by acting in advance, the controller minimises the effect of disturbances before they can alter the output. And there is no feedback loop in this case, the feed-forward system does not compare the actual output Y to the set point Y_{sp} for corrections. And this makes the system proactive rather than reactive.



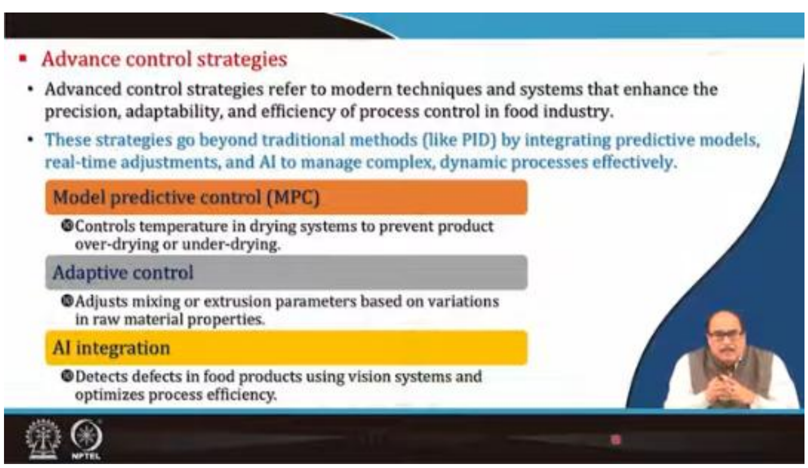
Fuzzy logic controller. It applies human-like reasoning to handle uncertainty and non-linearity in processes without requiring precise mathematical models. Instead of precise numerical inputs, it uses linguistic variables like low, medium, high, etc., to make control decisions. For example, regulating the baking process in an oven where parameters like temperature and baking times are adjusted dynamically based on the loaf size and other material characteristics. The advantages of fuzzy logic control include that it handles uncertainty and non-linear processes, mimics human decision making, is robust to variations and simplifies complex processes.



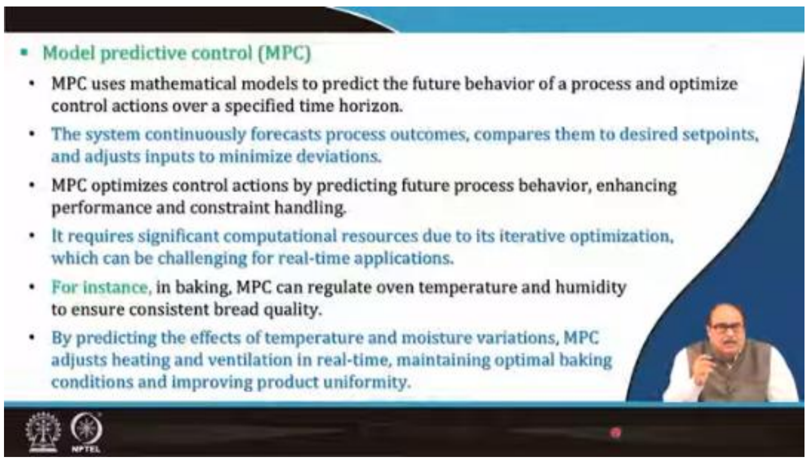
The working of fuzzy logic control, as you can see here in the figure, involves a fuzzification, which is the input stage. The fuzzy controller takes the input from the sensor right and converts it into a fuzzy value like low, medium or high, and then, for example, if the temperature is 180 degrees Celsius instead of 200 degrees Celsius, then it will say that yes, it is low. Then there is a rule-based decision-making stage, where a set of rules, like human logic, etc., are provided in the system, and then it decides what action to take based on the fuzzy input. For example, a rule could say that if the temperature is low and the baking time is increasing, increase the burner flame intensity. Then, based on this rule, the defuzzification, which is the output stage, converts back to a precise value to control the system that adjusts the burner flame. So, the temperature is raised. For example, based on the rule, the controller increases the flame intensity to bring the oven temperature back to 200 degrees Celsius for proper baking.



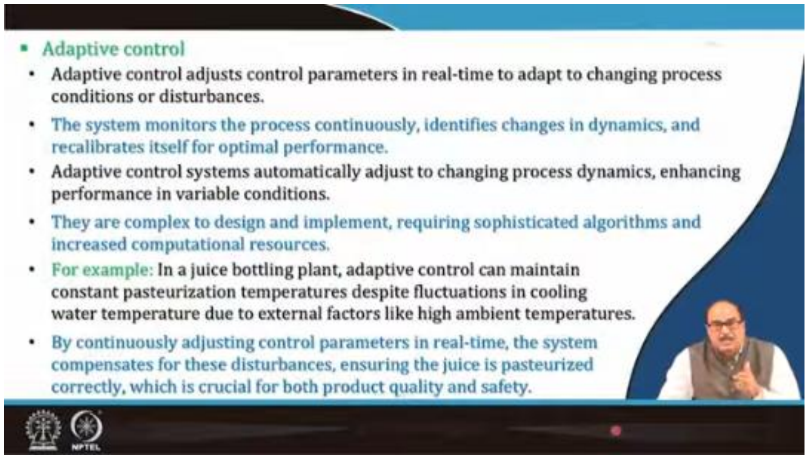
So, here again, if you have a comparison between these three control types- cascade control, feed work control and fuzzy logic control- the feed work cascade control receives a reactive, with a proactive secondary loop, whereas feed forward control, and fuzzy logic control are adaptive and heuristic; they handle non-linearity dynamically. Cascade control responds quickly to disturbances using the secondary controller. Feed-forward control eliminates any disturbances before they affect the process. Whereas fuzzy logic control handles uncertainty and dynamic changes effectively. But all three of these systems have certain limitations, like the cascade control system being slower than feed-forward for predicted disturbances. Feed-forward control systems need accurate process models and measurements, and fuzzy logic control systems are complex to design and implement.



So, advanced control strategies like these are modern techniques and systems that enhance the precision, adaptability, and efficiency of process control in the food industry. These strategies go beyond traditional methods like PID by integrating predictive models and real-time adjustments. and AI to manage complex dynamic processes effectively, and it may be model predictive controls, which control the temperature in drying systems to prevent product over-drying or under-drying or other such processes. Then, adaptive control, for example, adjusts mixing or extrusion parameters based on variations in raw material properties, and AI integration detects defects in the product, if there are any, using vision systems and optimises the process efficiency accordingly.

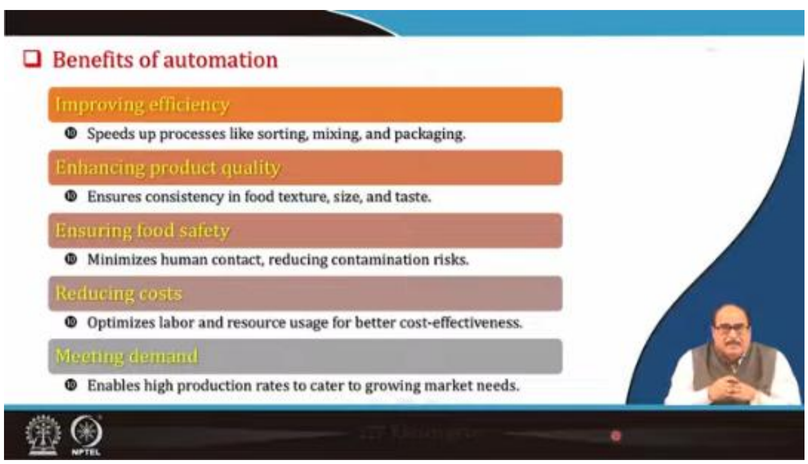


So, again, let us briefly discuss model predictive control. It uses mathematical models to predict the future behaviour of a process and optimise control actions over a specific time horizon. The system continuously forecasts process outcomes, compares them to desired set points, and adjusts inputs to minimise deviations. The model predictive control optimises control actions by predicting future process behaviour. It requires significant computational resources due to its iterative optimization, which can be challenging for real-time applications. For example, baking. The model predictive control can regulate oven temperature and humidity to ensure consistent bread quality. By predicting the effect of temperature and moisture variation, the model predictive control adjusts heating and ventilation in real time, maintaining optimal baking conditions and improving product uniformity.

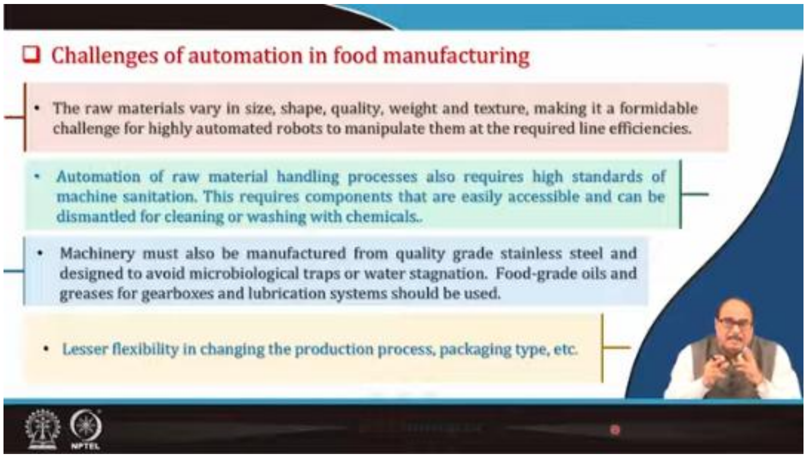


Adaptive control adjusts control parameters in real time to adapt to changing process conditions or disturbances. The system monitors the process continuously, identifies changes in dynamics, and recalibrates itself for optimum performance. For example, in a juice bottling plant, adaptive control can maintain constant pasteurisation temperature despite fluctuations in cooling water temperature due to external factors like high ambient temperature, etc. So, by continuously adjusting control parameters in real time, the system compensates for their disturbances, ensuring the juice is pasteurised correctly or the product outcome is better, which is crucial for both product quality and safety. So, AI integration, that is artificial intelligence, integrates machine learning algorithms and data analytics to make decisions, optimize processes, and improve efficiency. AI systems learn from real-time and historical data to predict outcomes, automate controls, and improve decision-making. Integrating AI into food processing enhances efficiency and product quality through automation and data-driven decision-making. However, sometimes, that is, integrating AI can be a costly system, and therefore, it may require significant investment in technology as well as better expertise to manage and control. For example, the prediction of equipment failure can be done through machine learning, and maintenance optimisation of ingredient ratios and quality control with AI-based vision systems can be done. However, one needs expertise to handle these things.

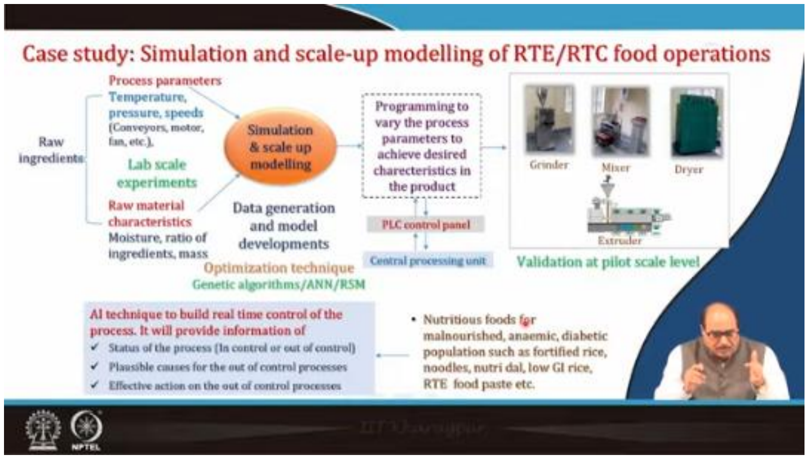
Then we talk about automation in the food industry, food manufacturing, and obviously, automation is the use of control systems, machines, and technology. to operate processes with minimal or no human intervention. And the food industry is moving towards automation nowadays, mainly due to increasing competition from globalisation and mergers, consumer demand for higher-quality foods, higher emphasis on cleanliness and hygiene, safety factors, and the high cost of insurance and compensation and flexibility in manufacturing for more diversified product lines. So, these are the drivers that drive the food industry toward automation. So, automation and robots essentially have the potential to transform operations like food manufacturing, handling, palletizing, packaging, storage, supply chain, and distribution, as well as in food serving. The details of this automation, and particularly the use of robots in the food industry, we will take up in the next class.



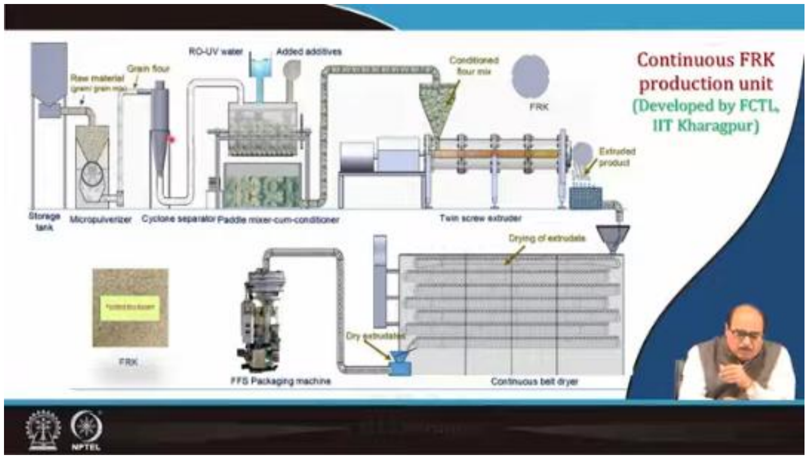
So, the benefits of automation. Obviously, it improves efficiency as it speeds up various processes or unit operations like sorting, grading, packaging, etcetera. It ensures consistency in food texture, size, and taste, and therefore enhances the product quality. It minimizes human contact, reducing the contamination risk, therefore ensuring better food safety. It optimises labour and resource usage for better cost-effectiveness. It enables high production rates to cater to growing market needs. So, these are some of the benefits which an industry can get by going for automation.



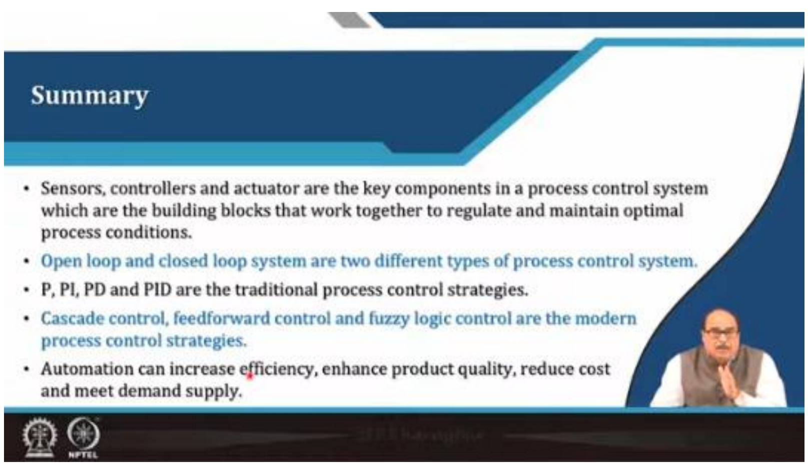
However, there are certain challenges in automation in food manufacturing. Number one, the raw material which we get. There may be a diverse, vast variety, even within the same material; there may be variations based on size, shape, quantity, weight, texture, etc. And this makes it a little difficult or a formidable challenge for highly automated robots to manipulate them at the required level of efficiency. Another example of automation of raw material handling processes, etc., like cleaning, also requires high standards of machine sanitisation. This is necessary because the raw material may be contaminated, particularly if you take fruits, vegetables, etc. So, their machine must be properly sanitised and cleaned after they use it, and this requires components that are easily accessible. And can be dismantled for cleaning and washing without the use of any chemicals or with the use of chemicals or sanitisers as the case may be. So, that is another challenge. Then, another challenge is their machinery. must also be manufactured from quality grade stainless steel and designed to avoid microbiological types or water stagnation, etc., inside the system. Even the food grade oils and greases, etc., for gear boxes and lubrication in the automated system, etc., should be used, and there should be less flexibility in changing the production processes. packaging type, etc., because once you have set the automated line, you cannot do much. So, this is again the challenge in the automation, which provides less flexibility in the production area.



So, I will now briefly take a case study that is pa rticularly about various processes which we have done in our course. Plant in our laboratory, etc., like for example, suppose you have different raw materials, and then there may be process parameters or raw material characteristics, like process parameters: temperature, pressure, speeds, etc. For these conveyors, motors, fans, etc., all are required to handle this, and then the raw material moisture ratio ingredients. So, all these things are taken into consideration for doing the live-scale experiments. One can use optimization techniques like genetic algorithm, ANN, RSM, etcetera, and you come up with some that is optimized optimum process and then go for the simulation and escape of modeling where data generation and model development can be done, and then these are the program to the of the pilot, whatever is optimized, okay. Then, programming to vary process parameters to achieve desired characteristics in the product, like a PLC control panel or central processing, etc. And this can send the signal for the pilot-scale validation, okay, because it may so happen that. Once that is for automation, you have to have a complete system on the basis of the lab model, we develop the things, and then we can give the desired input. Once it is done, part of pilot-scale nutritious foods, such as malnourished, anaemic, and diabetic, are various. Food product you can prepare that is lab-scale upscaling, then it is validating the model on the pilot-scale level. And then it gives that is the AI technique; it gives to build real-time control of the process, and it will provide information like the status of the process, whether it is in control or out of control. It may give plausible causes for all the out-of-control processes and then provide effective actions for the out-of-control processes. So, with this AI, you can get this input, and this input can then be taken into care while going for the large-scale or industrial production in an automated way.



So, this is how the continuous production of fortified rice kernel is designed as a continuous, automated process, like you have, where the broken rice, etc., from the storage tank comes. The micropulverizer rice is broken into flour, then with a suitable conveyor system, the rice flour is taken to the help of a cyclone automatically. It comes into the mixer mixer cum conditioner unit were added with the micronutrient and water etcetera. And then after conditioning this conditioned mixture of the rice flour and vitamin mineral premix, it is set in the extruder and the extruder is operated continuously. It gives the extruder rice kernels fortified rice kernels, which we talked about, and then it is set to the dryer automatically. And the dryer its speed, its conveyor belt size, etc., temperature, all those things are designed, and through controllers are there that input is given and it drives the product and then finally, set to the packaging line. So, the whole operation here is automated, and there is no human intervention.



So, with this, I would like to summarise this lecture that the sensor controllers and actuators are the key components in a process control system, which are the building blocks that work together to regulate and maintain optimal process conditions. Open-loop and closed-loop systems are two different types of process control systems. Proportional, proportional integrative, proportional derivative, and proportional integrative and derivative are the traditional process control strategies. Whereas, cascade control, feedforward control, and fuzzy logic control are the modern process control strategies. Automation, obviously, can increase efficiency, enhance product quality, reduce costs, and meet the demand-supply ratio. So, this obviously, once you go for the advanced control system, you will get a better output, particularly in the case of food, the food which is better in quality and meets better safety parameters, etcetera.

These are the references which were used in this lecture.

With this, I thank you very much for your patience. Thank you.