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Justify Improved Control via Process Economics – Part 1 of 3

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INTRODUCTION

Control technologists know that Advanced Regulatory Control (ARC) like cascade, ratio, feedforward, and nonlinear strategies can improve control, which leads to any combination of advantages such as increased throughput, reduction in energy consumption, improved quality, less waste, better operational efficiency, increased yield, less quality giveaway, and better safety margins.

But the scope of a control engineer is much wider than just control strategies. Improvements in the instrument system can also improve control. These include selecting the right type of instrument for the service, relocating measurements to reduce delay, improving resolution with higher bit processers, development of mathematical models of the process, inferential measurements, and linearizing transformations of models. Process changes can also improve control, such as increasing the level in a tank to increase in-line blending, placing positioners on flow control valves to prevent stiction, or removing assignable causes that periodically upset the process. Some of these improvements require additional investment and thus need economic justification.

"Improved control" is an abstract concept. Process improvements are often justified by a return-on-investment (ROI) metric. How does one forecast the economic benefits of improved control to justify a project? Then how does one assess the economic benefit in a post-implementation audit? How does one provide a comprehensive evaluation that includes robustness to upsets, ease of maintenance, or safety? One solution is to preview improvements on a digital twin, a mathematical model of the current process, validated with experimental data, which we can use to test the proposed control system.

Managers are risk adverse, skeptical, and need to be convinced that the proposed action will not result in safety issues, or complaints by operators, or maintenance issues when new folks become the control system operator. To them, what we might call an improvement could seem like a newfangled complexification. Managers know: "To a person with a hammer, everything looks like a nail." How can they be convinced that the proposed control improvement is not just a skill that the technologist wants to demonstrate as a self-gratification driver? Demonstrate the value of your proposed improvement using objective arguments based on the metrics they understand, like the ROI.

HOW TO ASSESS THE BENEFIT OF IMPROVED CONTROL

Improved control results in less variation in the controlled variable, which then permits operating closer to constraints, which permits higher throughput and/or less energy consumption, and thus more profit.

There are many ways that reduced variance can permit operating changes that improve the bottom line. Here are descriptions of two concepts:

Quality Give-Away

We would like to operate as near as possible to product specifications or operating constraints. But if the controlled variable (CV) has deviations from the set point, then to prevent violating specs or constraints, the set point must be moved away from the constraint. Figure 1 illustrates pressure control over time. The constraint is the upper horizontal dashed line, which might be related to equipment operating limits, and for process efficiency, we may wish to operate a distillation column nearer to the equipment pressure limit to get improved separation, to permit lower boil-up rates for the separation, which means lower energy consumption. On the left side of the figure, the set point (solid horizontal line) is much below the constraint to prevent the deviations on the CV (the noisy signal) from exceeding the constraint value. On the right side of the figure, improved control reduced the variation on the CV; and as a result, the set point can be moved nearer to the constraint, still preventing violations.

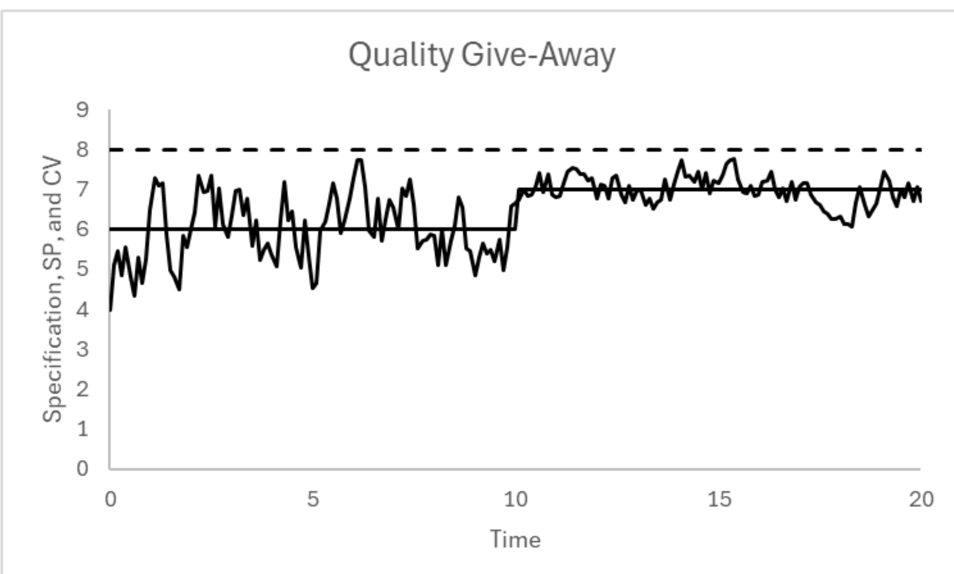

Figure 1 – Quality Give-Away Illustration

The set point deviation from the limit is termed quality give-away. Although the illustration represented pressure, the CV could be any number of variables. If the CV was an impurity in the product, to prevent specification violations, the producer must give the customer a higher quality product than is necessary. Hence the term quality give-away. Excess purity means higher raw material cost and/or higher cost processing – perhaps related to higher energy use in distillation, or higher residence time in a reactor, or higher levels of chemical treatment to separate the impurity.

Although Figure 1 represented pressure control, we still use the term quality give-away.

Regardless of the CV, given the reduction in variability, the process engineer should be able to use process models and intermediate product and utility values to estimate the processing cost advantage of the set point change related to the reduced variation. A question remains as to how to estimate the reduction in variability from a control or instrument improvement. An answer is coming. But first a look at another mechanism for process improvement.

Flooding

One type of flooding in a distillation column happens when a high velocity vapor up-flow entrains liquid droplets carrying them back up the column instead of letting them fall by gravity. The more liquid that is entrained, the less is the up-flow area, increasing the vapor velocity, exacerbating the entrainment effect. Eventually the liquid cannot fall through the column. The column fills with liquid, which is flooding. Basically, the vapor mass flow rate that causes flooding has a square root response to column pressure.

To increase production rate or to increase purity, the vapor flow rate needs to increase. However, the mass flow rate of the vapor is limited by the flooding point, and typically operation is kept safely below the flooding point so that process disturbances or imperfect control do not lead to flooding.

Figure 2 illustrates the pressure-to-flooding vapor rate relation and the limit on column pressure. The square root shaped curve indicates how the vapor mass rate that causes flooding (the maximum permissible vapor rate) depends on column pressure. The rightmost vertical dashed line at a pressure value of 38.5 is the pressure constraint on the equipment, and for a bit of a safety margin, we don’t want the pressure to exceed 37.5. The left most vertical dashed line represents the old pressure set point, and the bell-shaped curve on the bottom, centered on the “old SP” is the old operating column pressure distribution. Since the column pressure is variable, the set point must be adequately below the 37.5 limit so that the maximum pressure deviation does not violate the safe value. Roughly, the set point needs to be 3-sigma below the 37.5 limit, which is why the “old pressure SP” is at 35.5. But notice that the variation in pressure permits a low pressure of about 33.5, and this pressure determines the flooding velocity, the old vapor rate, labeled as “old limit”.

If a control improvement permits lower pressure variation, then the pressure set point can be moved closer to the constraint. Note that at the "new SP", with reduced variation, the maximum pressure does not exceed the limit of 37.5. Also note, that at the "new SP" the minimum pressure is now about 36, which defines the new upper limit on the vapor rate. In this illustration, improved pressure control permits about a 25% increase in vapor rate, which would translate to increased productivity for a given purity (additional profit), or increased purity for a given production rate (higher priced product grade).

Reduced pressure variation could also lead to diverse other benefits; such as those related to pressure constraints on the equipment, or thermodynamic separability.

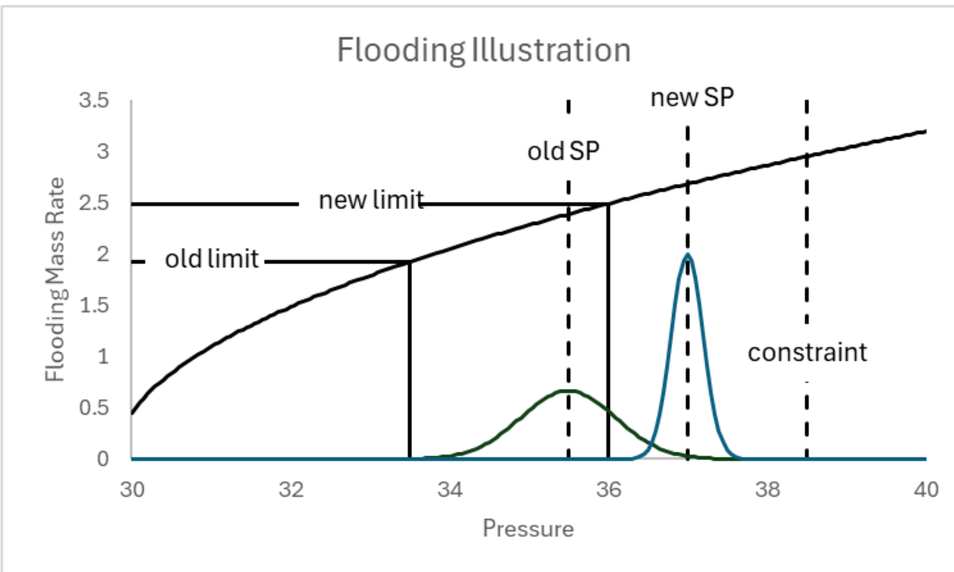

Figure 2 – Flooding Illustration

CLOSING

This, Part 1 of 3, opened with rational for using control technology to reduce process variability and two concept examples of how the reduced variability can translate to economic benefit. Part 2 will reveal several more examples and discuss the calculation methods. Part 3 will detail an application example.

ACKNOWLEDGMENTS

I greatly appreciate input on this article from Sandeep Lal, Sr. Process Control and Optimization Engineer, Chevron Phillips Chemical Co., LP. I also appreciate collaboration with Luis J. Yebra of the CIEMAT Research Centre on simulation and control projects supported in part by the Spanish Ministry of Science, and the European Union.

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Justify Improved Control via Process Economics – Part 2 of 3

R. Russell Rhinehart

This Part 2 of 3 continues to reveal concepts of how control technology to reduce process variability can translate to economic benefit.

Cavitation

When process liquid flows through devices that have a restriction (thermowells, orifices, valves, pumps), the fluid accelerates. Then exiting the device, flow rate returns to its normal velocity. From the Bernoulli effect, the locally higher velocity lowers the fluid pressure. Cavitation occurs when the pressure in a liquid falls below the vapor pressure or degassing pressure, which temporarily causes the fluid to flash boil or degas. Then, when exiting the device, the velocity reduces, the pressure increases, which causes the bubbles to collapse. The collapse causes the liquid on either side of the collapsing bubble to impact, and shock waves propagate through the liquid damaging the equipment. Higher production rates mean higher fluid velocity, which could lead to cavitation. Although it is not normally an issue, cavitation can limit throughput. Operating with cavitation is possible, but this reduces equipment life.

Cavitation could be eliminated by operating at higher pressure, which could be a control decision such as increasing the level set point in a tank or a design solution such as placing the device in an expander-contractor assembly. Or cavitation could be eliminated by operating at lower temperature. Or cavitation could be eliminated with improved control that reduces variation in throughput, pressure, or temperature. Whatever the solution, the increased production rate or extended equipment life could economically justify the process or set point change.

Sensor Reliability and Location

The control system depends on measurements. If the sensor tends to fail, lose calibration, has noise, has poor resolution, or is located in a place that causes a measurement delay (deadtime), then control will be degraded. Alternate sensors or locations or inferential measurements can solve those problems.

Blending

Increased blending of material in a process can reduce the impact of temperature or composition variation that comes from disturbances or feedstock variation. Blending could be in the preparation of feedstock, in-line mixing, longer or larger process lines, increased tank volume, or more effective tank agitation. As an ideal analysis related to quantity of material being mixed, the standard deviation of the mixed product composition scales with the inverse of the quantity. If volume or mass is doubled, the standard deviation of the PV (process variable) variation is halved.

Eliminate Assignable Causes

An "assignable cause" is an occasional external event that causes an upset to the process. It may be a sudden rainstorm that rapidly cools equipment, an occasional raw material batch that has an impurity, a measurement sensor failure, an electrical circuit trip, or many other singular events. It is not a continually operating influence on the process. Statistical Control Charts can reveal when some such event creates an unusual deviation from normal process variation. And then structured procedures (6-Sigma, SPC) can organize the search for the culprit event. Once identified, the process or management procedures can be changed to either eliminate such events or eliminate their impact on the process. The term "assignable cause" means that the source of the upset might not be known, but it has a statistically real impact on the process, and it can be identified.

Each time the impact of an assignable cause is eliminated, process variance is improved, with the associated benefits.

CALCULATION CHALLENGES

The concepts illustrated in Figures 1 & 2 of Part 1 and in traditional statistical control charts assume the classical Gaussian variation (normally distributed variation) in a process variable; however, nonlinearity in your process, interactions, or persistence of disturbances may make the PV variation non-Gaussian. In this case, classic metrics of variation (variance, and standard deviation), classic statistical procedures (t- or F-test, ANOVA), or classic linear regression may be invalid.

If one can determine the pattern of the deviations from set point, and the reduction in the distribution due to improved control, then one could determine the economic benefits of control improvements in the process, which permit operating closer to constraints.

A classic heuristic rule is that each advance in control strategy halves the PV variation. But it may, or may not.

So, the question is, "How to assess the impact of control improvements on variability, and from that the impact on process economics?" An answer is to use process simulation.

USE PROCESS SIMULATION

A systematic way to calculate improved control benefits is by using process dynamic simulators, which are grounded in accurate models and validated with process data.

In modern parlance, a dynamic simulator that is a surrogate for the process is called a “digital twin”. Include environmental effects to the simulator (noise, drift, stiction, resolution, etc.) to make the simulation representative of what Nature will give you. A simulation including natural vagaries is termed a stochastic simulation. By contrast, most simulations are deterministic. When your process is operating, Nature does not keep the inlet humidity, fuel BTU content, ambient losses, or catalyst reactivity constant. And Nature contrives mechanisms that add noise to measurements.

Simple models for generating noise and disturbances are presented in the references [1, 2, 3].

Calibrate your digital twin and its input disturbances so that the simulator matches the variation you currently have in your process.

From extended time simulation, measure the frequency and magnitude of specification violations, waste generation, on-constraint events, and consumption of material and utilities. Then, change the simulator to represent control improvements that you are considering, and run it for an extended time to reveal the new CV and PV distributions, which will allow you to explore set point changes that will result in reduced operating expenses or improved throughput. Run it with the new set points to assess the variation and improvements in quality, throughput, etc.

Use the results of the simulated current operation that match current process values to establish credibility of the simulator with your customers, then use the before and after results to credibly reveal the economic impact of your proposed control improvement.

CLOSING

This, Part 2 of 3 revealed several concept examples of how reduced variability from control can translate into an economic impact. Part 3 will detail an application example.

ACKNOWLEDGMENTS

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Justify Improved Control via Process Economics – Part 3 of 3

R. Russell Rhinehart

This third part of the series shows how simulation can be used to quantify the reduced variation that results from improved control, and how to assess the associated economic benefit.

EXAMPLE

The Plataforma Solar de Almeria, Spain is a full-scale CIEMAT research center, exploring several approaches to generate electricity from thermal collection of solar energy. CIEMAT (Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas) is a Spanish public research organization focused on energy, environment, and technology. An aerial view of the TCP-100 facility, Figure 1, shows the parabolic trough collection (PTC) approach. Mirrors in the parabolic trough focus solar energy on a pipe that runs along the focal point of the mirrors. Oil is heated as it runs through the pipe, and the hot oil is then used to generate superheated steam to run a turbo-generator to generate electricity.

Figure 1 – An arial view of the collection lines of the TCP-100 facility

There are three lines that loop north then south in the TCP-100 facility. Each line has a total collection length of about 96 m. The mirrors change orientation during the day as they track the sun. Direct Normal Irradiance (DNI) is the intensity of solar energy falling on the aimed mirrors, and it nominally changes from about 400 to 1,000 and back to 400 W/m^2 during the day, but the value is also affected by temporal atmospheric events (mainly clouds). There are some ambient losses in each line, which depend on random changes in both wind and ambient temperature. And for many reasons (fouling, dirt, mirror damage, sun angle, mirror aim, etc.)

the optical efficiency of each line is unique and changes over time. Similarly, fluid friction loss factors change independently in each line due to changes in fouling, and other in-line effects.

Variable speed pumps feed return oil to the header for the solar collection lines. Valves in the lines adjust the flow rates to make the exit temperature match a target, and pump speed is also adjusted to minimize parasitic power losses.

Currently however, industrial solar thermal plants have a low level of automation, largely because complex control systems that would objectively demonstrate improved efficiency have not yet been developed. This study is part of one research effort.

One control challenge is that of temperature control in the thermal collection line due to long and variable transport delays (2 to 5 minutes), several nonlinearities, and continual uncontrolled input disturbances. Another is the minimization of pump power consumption (parasitic losses).

Figure 2 presents how DNI changes during a nominal day (with the solar peak at noon). The perturbations in the DNI trace (the dashed line) are due to random walk perturbations driven by Gaussian noise. See references [2] or [3] for the models. The drifting influences were calibrated to mimic actual field measurements. Since we cannot know the Truth about Nature, we measure process variables, but measurements have calibration error, so the information that the controller has is not the true DNI but the somewhat erroneous measured value, which is the middle trace in Figure 2. Ambient heat losses, inlet oil temperature, and pipe friction factors, each have individual characteristic drift and measurement error.

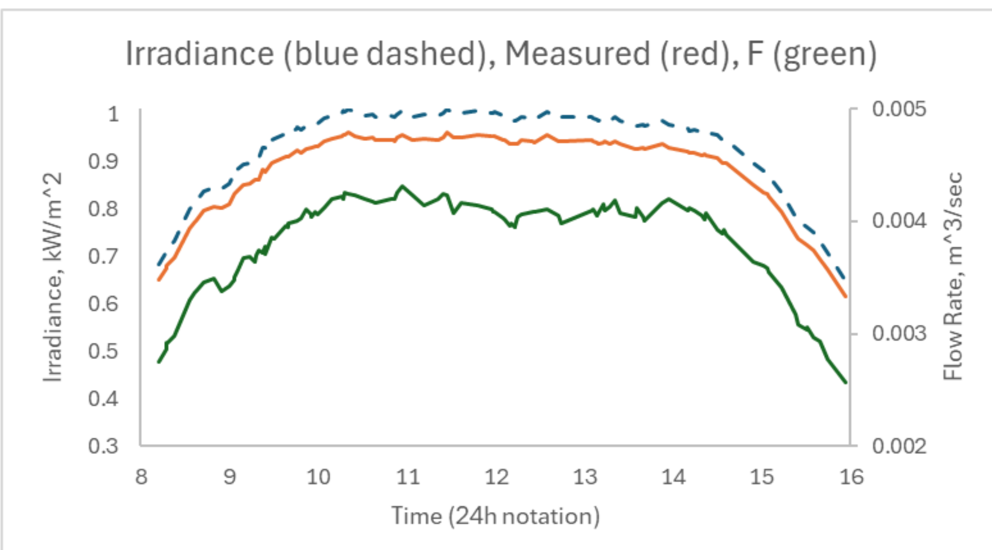

Figure 2 – True and measured DNI and controlled flow rate measurement during a nominal day.

The main control objective is to keep the exit oil temperature at a set point. As DNI changes during the day, so must the oil flow rate, which is the lower trace in Figure 2. The perturbations on it are larger than what the DNI alone would suggest, because of the simulated variation in ambient losses and inlet temperature.

The initial control strategy investigated was PI feedback on the exit oil temperature measurement and feedforward correction based on the measured inlet oil temperature. It worked acceptably for the conditions for which it was tuned (without significant variations in the DNI, inlet T, or ambient losses). But, as the day progresses the flow rate creates about a 2:1 change in the delay, and the process gain also has about a 2:1 ratio. Gain scheduling seemed to be a possible solution, but the number of scheduling factors for each of the 6 PI and FF tuning coefficients seemed to violate the K.I.S.S. principle.

So, we next investigated the use of a nonlinear feedback controller on the exit oil T cascading a flow rate set point to a nonlinear flow controller. The T controller used Generic Model Control (GMC) with a steady state model. This is equivalent to classic advanced regulatory output characterization [3]. The model in GMC includes feedforward compensation for the inlet T. The primary GMC Temperature controller sent a set point value to the secondary model-based flow controller, which uses a simple dynamic model for the flow rate response to the signal sent to the valve. This strategy is relatively simple, with only 2 tuning coefficients for GMC and 1 for MBC, and it kept the exit temperature within +/- 1 ^{o}C of the set point during the simulated day.

Midline temperature would provide an early indication of the impact of disturbances (inlet T, DNI, and ambient losses) on the exit T. This suggests another level of cascade control. In this strategy, the exit T controller sends a set point to the mid-line T controller, which sends a set point to the flow controller, which operates the valve. Since mid-line T is nearly a linear indication of exit line T, we used a PI controller for the exit T, cascading to the GMC controller for the mid-line T, cascading to the model-based flow controller. In total there are 5 tuning coefficients, and over the simulated day, control kept the exit T within +/- 0.3 ^{o}C of the set point. This is an advantage because precise T control permits operating close to constraints for oil degradation and boiler performance. However, in this case, the improvement in net power that could be generated by operating 0.7 ^{o}C closer to a constraint is within the noise.

Finally, we explored a supervisory adjustment of pump speed, with a simple logic to adjust speed to keep valve at about 95% open to minimize parasitic energy loss. If the pump remains at full speed during the day, then the valve must throttle flow rate to control temperature. This requires greater pump power than is necessary. By reducing pump speed if the valve is less than 92% open and increasing pump speed if the valve is over 98%, the valve is kept at about 95% open providing some immediate control flexibility, while minimizing parasitic losses. Figure 3 indicates how the signal to the valve and pump speed (as a fraction of maximum) change during the simulated day. Compared to operating the pump at 100% speed during the day, this action reduces parasitic losses by about 25%, which is significant.

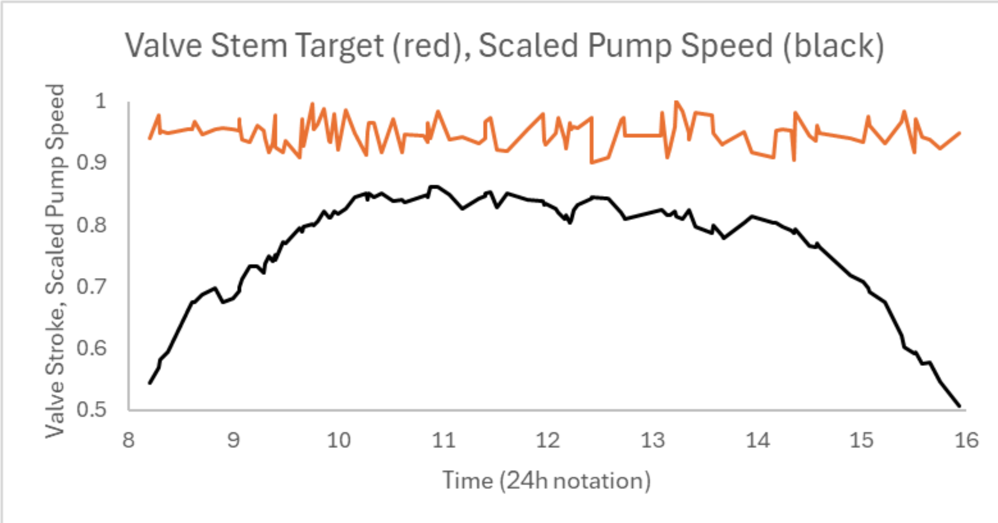

Figure 3 – Pump speed and valve position for a simulated day

This example reveals that simulation can be used to investigate alternate control strategies, quantify the reduction in CV variation, and quantify the resulting economic benefit (in this example the operating power consumption.)

CONCLUSION & PERSPECTIVE

The domain of control engineering is more than control algorithms. It includes the instrument system, process optimization, dynamic and steady state simulation, calibration, design, equipment selection, coding, device communication, and the standards for each. Develop your potential in all aspects of the profession to add value as a control engineer.

Use simulation to explore and quantify the economic benefits of improved control.

Simulators are not free. They could be comprised of phenomenological models that range from rigorous to first-principle types. They could include empirical models for some elements of the process. They could be steady-state design models that are adapted to represent dynamics with simple linear dynamic add-ins. In any case, digital twins require engineering effort to create, to update as the process changes, and to validate against process data. But once you have a digital twin, it serves many engineering endeavors such as process trouble shooting, inferential process monitoring, design, personnel training, preservation of mechanistic process knowledge, and, of course, process control.

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Spanish Ministry of Science, and the European Union ("*Digital twin analysis of Solar) Parabolic trough collector plant to scale to higher powers for the integration into Electrical Distribution network* (DISOPED)", ref: PCI2022-134974-2), and "*Modelling and diagnosis of parabolic trough collectors* (MODIAG-PTC)", ref TED2021-129189B-C21/TED2021-129189B-C22).

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