Understanding and Applying Simulation Fidelity to the Digital Twin

Introduction

Selecting the level of process model fidelity for the Digital Twin requires careful consideration. Although it is not the only aspect of the simulator investment to consider, it is an important one. Process model fidelity can have a significant impact on the lifecycle utility of the dynamic simulator as well as the lifecycle support cost of the solution. In this paper, we discuss several aspects of process model fidelity by reviewing the following:

- Types of Process Models - Steady-State, Dynamic, Real-Time
- Process Modeling Techniques - First Principles and Empirical Modeling
- Levels of Process Model Fidelity
- Applying Levels of Process Model Fidelity
- Physical Fidelity Considerations
- Dynamic Simulator Performance

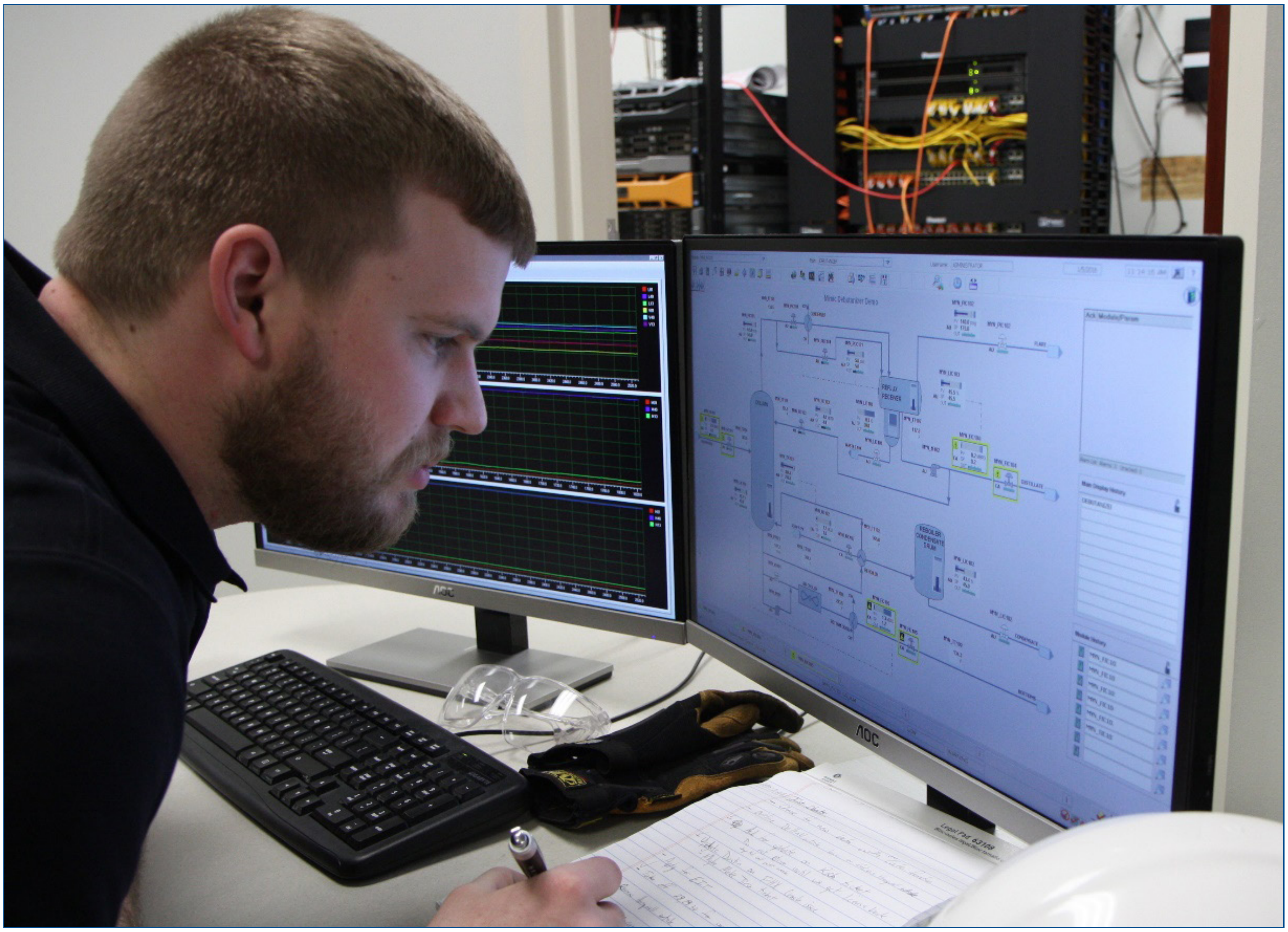
Types of Process Models

Digital Twins require process models that are dynamic and real-time. The characteristics of process models can be summarized as follows:

Steady-State models are used for plant equipment sizing and process design. Inputs to these models are pressures, temperatures, flows, and compositions; and outputs are equipment sizing and process optimizations. These models can be very complex (or high fidelity), but a steady-state model does not simulate transitions between process states including time delays, deadtimes, or mass holdups.

Dynamic models use equipment sizes and specifications for inputs with outputs of pressures, temperatures, levels, flows, and compositions. They are time based and resolve transitions between process states. Outputs to the model are affected by the inputs along with the time delays and deadtimes of the model. Holdups and mass are calculated with the result of a dynamic material, energy, and momentum balance.

Real-time models are a sub-set of dynamic process models. A real-time model must converge or resolve at a fast enough cycle to allow updates to the control loops and operator console identical to the real plant.



Dynamic, real-time process models are required for the Digital Twin.

The use case of the Digital Twin requires the application of **real-time** and **dynamic** process models. Steady-state simulation platforms are not usable, and many dynamic simulation offerings do not support real-time performance. Mimic was designed for the dynamic, real-time model requirements of the Digital Twin, providing a Lifecycle Dynamic Simulation for our users.

The industry is increasingly recognizing the value of using simulation for the entire project cycle. The term Multi-Purpose Dynamic Simulation (MPDS) describes this approach. Some of the use cases in MPDS requires real-time dynamic models but some do not. For instance, process design studies may not require real-time models, but operator training will. With the AspenTech Emerson alliance, Mimic integrated with HYSYS Dynamics supports the user who wants to apply a MPDS approach.

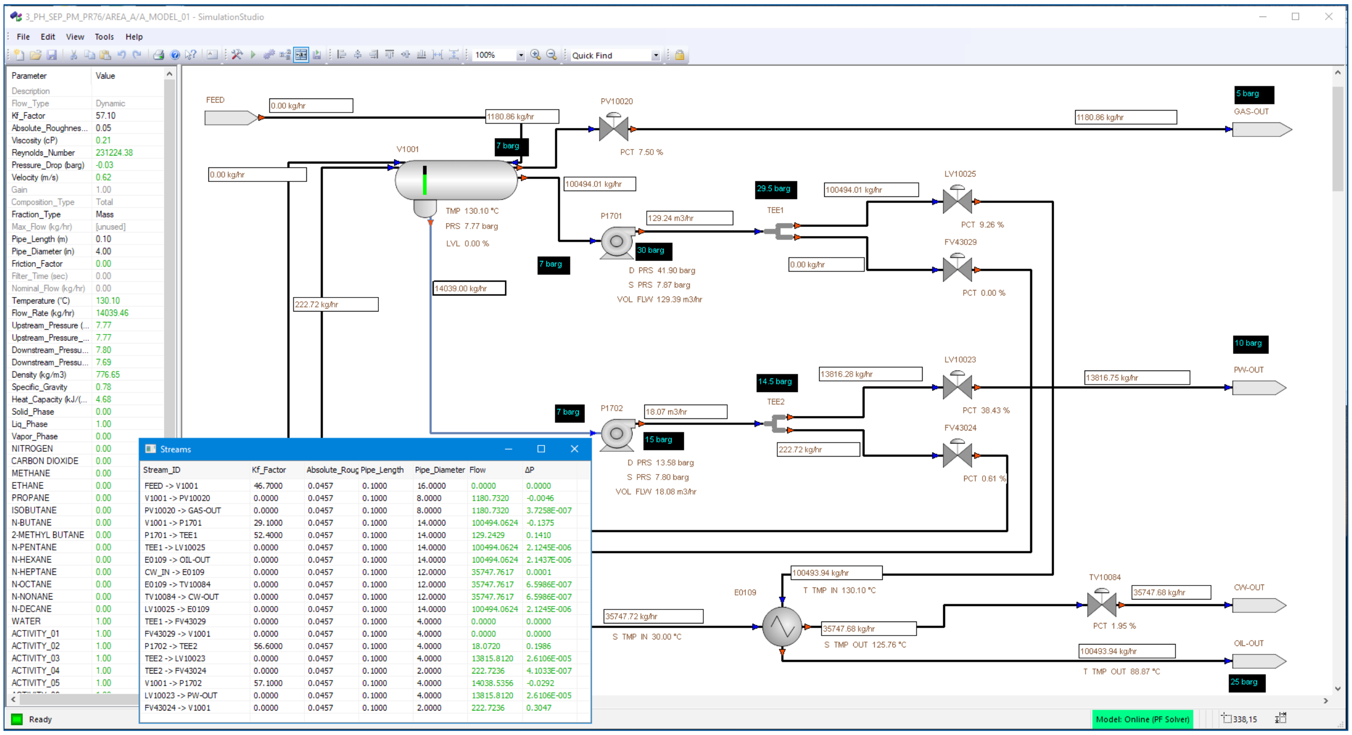
Process Modeling Techniques

First Principle is a term that is often used interchangeably with high fidelity process models. This is a misuse of the term as “first principle” defines the type of the model versus the complexity or performance. First principles modeling is more correctly defined as a simulation based upon laws of conservation of mass, energy, or momentum using physical and chemical characteristics of the process.

Empirical or data-driven modeling refers to the use of historical process data or other performance correlations to calculate process variables using polynomial equations or more complex algebraic constructs.

Unless the application can settle for a low fidelity modeling complexity, dynamic simulation should be based upon first principles models and not rely solely upon empirical models. A first principles basis will ensure that mass and energy are conserved over the maximum operating conditions, providing directionally correct, realistic results. A model based upon empirical correlations (data-driven) will likely only operate well under the operating conditions of the data used for the model and may fail outside of this range.

Historical process data can and should be used to *tune* a first principles model to more closely resemble an actual operating plant. For example, tuning with historical data can show actual performance for fouled heat exchangers or piping models that do not behave per the plant design data. However, a well-designed first principles model using the actual equipment design data from the plant will require less tuning and will always provide the best performance.



Parameter	Value
Description	
Flow_Type	Dynamic
Kf_Factor	57.10
Absolute_Roughnes...	0.05
Viscosity (cP)	0.21
Reynolds_Number	231224.38
Pressure_Drop (barg)	-0.03
Velocity (m/s)	0.62
Gain	1.00
Composition_Type	Total
Fraction_Type	Mass
Max_Flow (kg/hr)	[unused]
Pipe_Length (m)	0.10
Pipe_Diameter (in)	4.00
Friction_Factor	0.00
Filter_Time (sec)	0.00
Nominal_Flow (kg/hr)	0.00
Temperature (°C)	130.10
Flow_Rate (kg/hr)	14039.46
Upstream_Pressure (...	7.77
Upstream_Pressure_...	7.77
Downstream_Pressu...	7.80
Downstream_Pressu...	7.69
Density (kg/m3)	776.65
Specific_Gravity	0.78
Heat_Capacity (kJ/(...	4.68
Solid_Phase	0.00
Liq_Phase	1.00
Vapor_Phase	0.00
NITROGEN	0.00
CARBON DIOXIDE	0.00
METHANE	0.00
ETHANE	0.00
PROPANE	0.00
ISOBUTANE	0.00
N-BUTANE	0.00
2-METHYL BUTANE	0.00
N-PENTANE	0.00
N-HEXANE	0.00
N-HEPTANE	0.00
N-OCTANE	0.00
N-NONANE	0.00
N-DECANE	0.00
WATER	1.00
ACTIVITY_01	1.00
ACTIVITY_02	1.00
ACTIVITY_03	1.00
ACTIVITY_04	1.00
ACTIVITY_05	1.00

Streams

Stream_ID	Kf_Factor	Absolute_Roug	Pipe_Length	Pipe_Diameter	Flow	ΔP
FEED -> V1001	46.7000	0.0457	0.1000	16.0000	0.0000	0.0000
V1001 -> PV10020	0.0000	0.0457	0.1000	8.0000	1180.7320	-0.0046
PV10020 -> GAS-OUT	0.0000	0.0457	0.1000	8.0000	1180.7320	3.7258E-007
V1001 -> P1701	29.1000	0.0457	0.1000	14.0000	100494.0624	-0.1375
P1701 -> TEE1	52.4000	0.0457	0.1000	14.0000	129.2429	0.1410
TEE1 -> LV10025	0.0000	0.0457	0.1000	14.0000	100494.0624	2.1245E-006
E0109 -> OIL-OUT	0.0000	0.0457	0.1000	14.0000	100494.0624	2.1437E-006
CW_IN -> E0109	0.0000	0.0457	0.1000	12.0000	35747.7617	0.0001
E0109 -> TV10084	0.0000	0.0457	0.1000	12.0000	35747.7617	6.5986E-007
TV10084 -> CW-OUT	0.0000	0.0457	0.1000	12.0000	35747.7617	6.5986E-007
LV10025 -> E0109	0.0000	0.0457	0.1000	14.0000	100494.0624	2.1245E-006
TEE1 -> FV43029	0.0000	0.0457	0.1000	4.0000	0.0000	0.0000
FV43029 -> V1001	0.0000	0.0457	0.1000	4.0000	0.0000	0.0000
P1702 -> TEE2	56.6000	0.0457	0.1000	4.0000	18.0720	0.1986
TEE2 -> LV10023	0.0000	0.0457	0.1000	4.0000	13815.8120	2.6106E-005
TEE2 -> FV43024	0.0000	0.0457	0.1000	2.0000	222.7236	4.1033E-007
V1001 -> P1702	57.1000	0.0457	0.1000	4.0000	14038.5356	-0.0292
LV10023 -> PW-OUT	0.0000	0.0457	0.1000	4.0000	13815.8120	2.6106E-005
FV43024 -> V1001	0.0000	0.0457	0.1000	2.0000	222.7236	0.3047

Ready

First Principle Process Models should always be used for Dynamic Simulators.

Levels of Process Model Fidelity

Depending on the goals of the simulator, a higher or lower fidelity model may be required. It is both the most cost and time effective to choose model fidelity based on the specific needs of the project and apply distinct levels of fidelity, as needed, for different process areas or at various stages of the project. The simulation platform used should be capable of selectively applying model fidelity as needed from low to high.

A description of each fidelity category is as follows and is shown in the table below:

Tiebacks – As the lowest level of models, tieback models provide output to input response for process loops and discrete devices. In a tieback solution, uncontrolled IO will usually have static values only. This level of modeling is generally acceptable for control system database and graphics testing. It has the lowest implementation and maintenance cost.

Low Fidelity - In addition to the tieback base, this approach adds data correlations to provide directionally correct responses for all IO, based upon process dynamics. Modeling would be empirical only but dynamic response for individual loops could be relatively accurate. Applying this level of model to operator training or control system testing requires user intervention to make it respond correctly to automation system actions.

Medium Fidelity - This term has been used to define many levels of process modeling between low and high fidelity. Emerson's **Dynamic Core** approach to medium fidelity, applies a first principle model that incorporates conservation of mass and energy as well as a pressure/flow network solver, on top of a Tieback and IO model foundation. Medium fidelity approaches, like **Dynamic Core**, can be a good compromise of performance and lifecycle cost, as this model will run automatically and respond to automation system actions and process changes.

High Fidelity – The highest level incorporates rigorous mass balance, rigorous heat balance, vapor-liquid equilibrium and reaction kinetics. In high fidelity simulations, process streams are modeled with individual component tracking and thermodynamic properties. The value of high fidelity process models is more realistic performance and dynamic transitions over a full operating range. The model will run automatically and respond to automation system actions and process changes in a very similar manner to the designed process. In general, high fidelity model development will require more process design data up front and may have a higher lifecycle cost.

	Process Model Fidelity			
mimic Capabilities	Tiebacks	Low	Dynamic Core	High
Static Values for Uncontrolled I/O	✓	✓	✓	✓
Directionally Correct Process Response for Loop I/O	✓	✓	✓	✓
Directionally Correct Process Response for Dynamic I/O		✓	✓	✓
Simple I/O Interactions		✓	✓	✓
Material and Energy Balance			✓	✓
Pressure-Flow Network			✓	✓
Equipment Modeled per Plant Design Specifications			✓	✓
First-Principles Based Process Interactions			✓	✓
Component, Phase, and Size Tracking				✓
Vapor-Liquid Equilibrium				✓
Reaction Kinetics				✓
Realistic Transitions over Full Operating Range				✓

Process model fidelity can be specified based upon model characteristics from tiebacks to high.

Applying Levels of Process Model Fidelity

Applying the correct level of process model fidelity can be difficult with an incorrect approach resulting in wasted time and money. On one hand, specifications often dictate a high fidelity model while neglecting the requirements of dynamics and real-time response. This is usually because the submitting engineer has confused the use and requirements of a steady-state design model with the needs of a Digital Twin.

Alternatively, some claim that successful operator training exercises can be conducted with simplified lower fidelity models. While many operator training exercises can be carried out with a simple model (some can also be carried out without a control system simulator for that matter), that does not diminish the value of higher fidelity models.

Greg McMillan in **Exceptional Opportunities in Process Control - Virtual Plants** developed a five level definition of model fidelity based upon the purpose of the simulator (or opportunity). Greg's approach has evolved into eight applications for a Digital Twin with the required model fidelity for each level, as shown in the table below. The user can easily correlate the application of the simulation to the process model requirements using Greg's definition. Following this approach will allow the user to develop a solution that blends the best combination of performance, cost, and time to market.

	Process Model Fidelity			
mimic Simulation Applications	Tiebacks	Low	Dynamic Core	High
Test Fundamental Control System Configuration	✓	✓	✓	✓
Familiarize Operators with Control System Interface	✓	✓	✓	✓
Familiarize Operators with Control Strategies		✓	✓	✓
Rigid Training with Programmed Process Response		✓	✓	✓
Test Control Strategies			✓	✓
Training on Simple Process Upsets & Operating Procedures			✓	✓
Loop Tuning & Simple Control Parameter Studies				✓
Training on Process Interactions, Upsets & Operating Conditions				✓

Process model fidelity should be selectively applied based upon the user requirements or application.

Physical Fidelity Considerations

An important aspect of building the Digital Twin is ensuring the physical or environmental fidelity is not compromised. This is especially critical for the application of using the lifecycle dynamic simulator for operator training. Physical Fidelity refers to the level at which a simulator resembles the environment used by the student or trainee. In the case of operator training or control system testing, this refers to how accurately the simulator operator station resembles the operator station in the actual plant. Compare this to an airplane flight simulator where the cockpit of the simulator is identical to the cockpit of the plane. In order to meet this requirement, most control system vendors have a control system simulator offering that allows the exact same graphics, faceplates, controls, and alarms to be copied to the simulated environment. Using a control system simulator is the preferred approach to implementing operator training systems because it allows plant operations to learn how to manage the plant in the exact physical setting that exists in the control room.

Good physical fidelity is essential for flight simulators and process plant operator training systems.

Physical or environmental fidelity is also very important for other use cases of the Digital Twin. Automation improvement, operational & safety studies, and other operational improvements all rely upon using the control algorithms, configurations, and data representations shown in the actual plant. To that extent, a strict adherence to 100% physical fidelity in the control system simulation allows the user to improve the operation of the plant without impacting the actual plant and reduces the risk of transferring operational improvements from the simulator to the real plant. Achieving physical fidelity requires the following in the deployment of a Digital Twin or dynamic simulator:

- No additions or deletions to the control system configuration for the purposes of simulation. This requirement excludes the dated practice of adding simple models to the control system configuration.
- Non-intrusive IO simulation that stimulates the IO of the control system simulator with, again, no changes to the control system configuration.
- Management of change practices that keep the control system in the plant and in the simulation synchronized. Ideally, the dynamic process simulator platform should have utilities that make this practice simple and require minimum manpower.

The Digital Twin and Dynamic Simulator Performance

Model fidelity is important, but a decision on model fidelity does not necessarily dictate solution accuracy. When considering the needed performance of a Digital Twin the user should be careful to consider the requirements of the application. In addition, the following guidelines will help ensure the solution meets the needs of the application.

Use actual unit operation design data

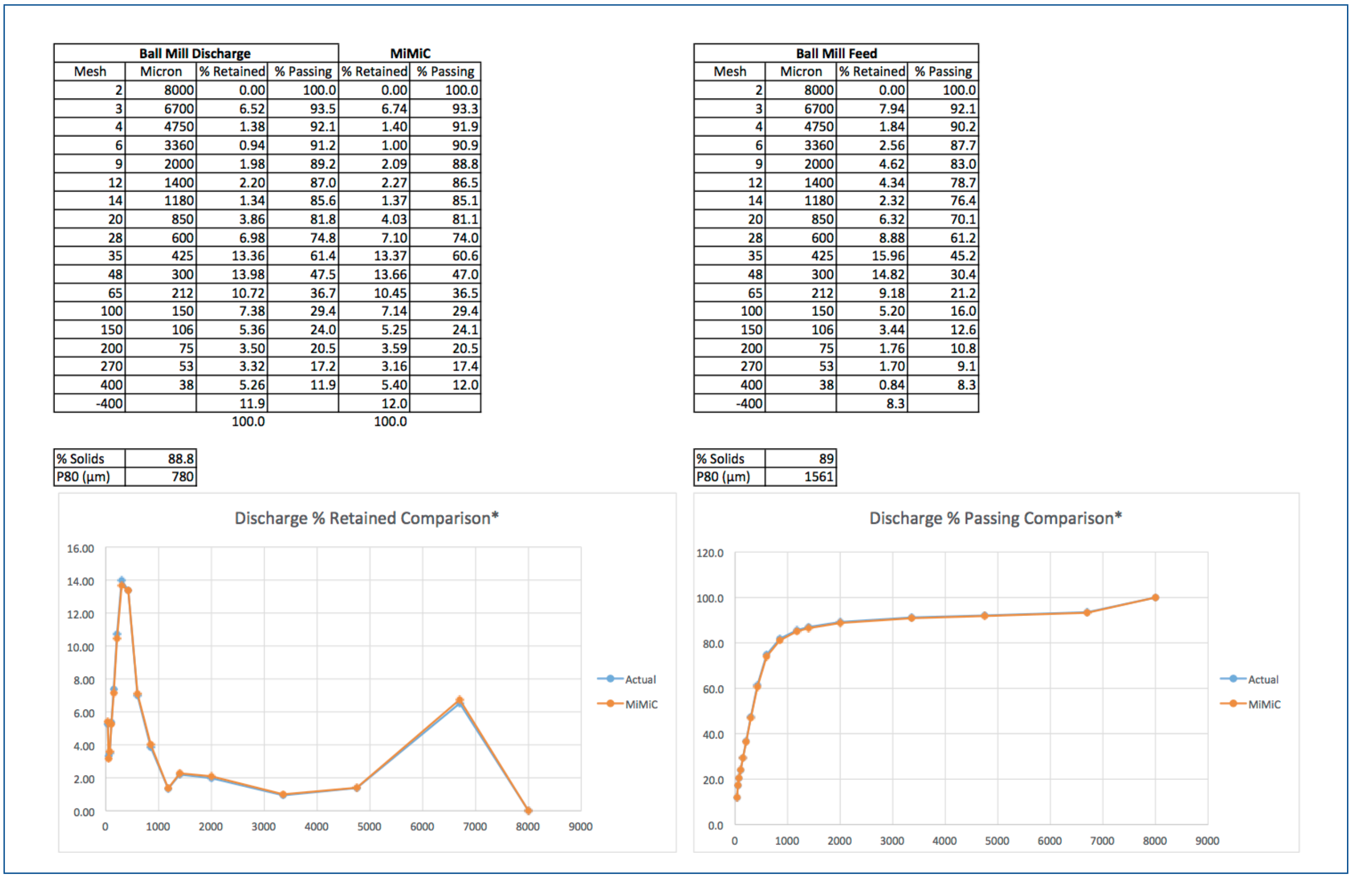
A first principles unit operations model based upon proven chemical engineering methods should be the basis for the simulation. When configured using the design data from the unit operation and the plant, the resulting model should provide dynamic responses like the actual equipment. Starting with a first principles model and using good plant design data will make it easier to meet your simulator performance.

Be careful with steady-state process design software predictions

Basing dynamic simulator performance on process values from steady-state design models can be problematic. There is a misperception in the industry that the results calculated by some process design software modeling packages are without error. A knowledgeable user of these packages will tell you that you can change the results calculated by the steady-state models significantly by how you configure the models. For instance, changing the thermodynamic properties package used by the model can dramatically change the calculated results. Comparison to a design package does not ensure that the model will accurately represent the actual process.

Use plant historical data for the final performance criteria

The performance data extracted from the process historian is the only valid basis for assessing simulator accuracy. However, because no process responds exactly like first principles equations, the dynamic models need to be tuned using empirical plant or design data. Tuning and testing the models will require good comparison test cases derived from actual plant historical data. Care must be taken to ensure that the data for comparison is gathered under conditions and operating states that are identical to the configuration and current operation of the simulator. In general, you should be able to achieve a steady-state 5% accuracy of physical variables (pressure, flow, temperature, level) with a reasonable amount of tuning. Greater steady-state accuracy can be achieved with more attention to tuning. However, it is important to determine the requirements of the system up front to avoid wasting excessive time tuning values to achieve the unnecessary (and impossible) goal of a “perfect simulator”.



Ball Mill Discharge				MiMiC	
Mesh	Micron	% Retained	% Passing	% Retained	% Passing
2	8000	0.00	100.0	0.00	100.0
3	6700	6.52	93.5	6.74	93.3
4	4750	1.38	92.1	1.40	91.9
6	3360	0.94	91.2	1.00	90.9
9	2000	1.98	89.2	2.09	88.8
12	1400	2.20	87.0	2.27	86.5
14	1180	1.34	85.6	1.37	85.1
20	850	3.86	81.8	4.03	81.1
28	600	6.98	74.8	7.10	74.0
35	425	13.36	61.4	13.37	60.6
48	300	13.98	47.5	13.66	47.0
65	212	10.72	36.7	10.45	36.5
100	150	7.38	29.4	7.14	29.4
150	106	5.36	24.0	5.25	24.1
200	75	3.50	20.5	3.59	20.5
270	53	3.32	17.2	3.16	17.4
400	38	5.26	11.9	5.40	12.0
-400		11.9		12.0	
		100.0		100.0	

% Solids	88.8
P80 (µm)	780

Ball Mill Feed			
Mesh	Micron	% Retained	% Passing
2	8000	0.00	100.0
3	6700	7.94	92.1
4	4750	1.84	90.2
6	3360	2.56	87.7
9	2000	4.62	83.0
12	1400	4.34	78.7
14	1180	2.32	76.4
20	850	6.32	70.1
28	600	8.88	61.2
35	425	15.96	45.2
48	300	14.82	30.4
65	212	9.18	21.2
100	150	5.20	16.0
150	106	3.44	12.6
200	75	1.76	10.8
270	53	1.70	9.1
400	38	0.84	8.3
-400		8.3	

% Solids	89
P80 (µm)	1561

High fidelity dynamic simulation performance compared to plant historical data for mineral processing ball mill.

Balance steady-state accuracy versus dynamic performance

The only industry wide specification that addresses dynamic simulator performance is *ANSI/ISA specification 77.20.01-2012, Fossil Fuel Power Plant Simulators – Functional Requirements*. Section 6.1 states the following performance criteria for steady-state accuracy:

> *"As a minimum, the simulator-computed value of critical parameters for steady-state, full power operation with the reference plant control system configuration shall be stable and shall not vary more than 2% of the measuring instrument range as observed in the reference plant."*

The specification makes the following statement in section 6.2 for dynamic performance defined as during transient operation:

> *"Transient operations include malfunctions, abnormal operations, and any non-steady-state plant condition. Simulation performance under transient conditions shall meet the following criteria:*
>
> *Where applicable, it shall be the same as the plant start-up test procedure acceptance criteria.*
>
> *The observable change in the parameters shall correspond in direction to those expected from a best estimate for the simulated transient and shall not violate the physical laws of nature.*
>
> *The simulator shall not fail to cause an alarm or automatic action if the reference plant would have caused an alarm or automatic action, and, conversely, the simulator shall not cause an alarm or automatic action if the reference plant would not have caused an alarm or automatic action.*
>
> *The overall system transient characteristics' time shall be within 20% of the reference plant when under the same operating conditions."*

The requirements for dynamic performance are much looser than steady-state performance for good reason. When measuring simulator performance during transient or dynamic conditions, it can be difficult to create an accurate environment of comparison. Getting all the factors that influence the models the same as the factors that influence the real process is problematic. Test cases developed for the Digital Twin need to be practical and operations focused and avoid imposing steady-state design simulator requirements.

Focus on dynamic, real-time response

One of the goals of investing in simulation is to train the plant operator on the safe and effective operation of the plant during malfunctions, abnormal operations, and startups /shutdowns. In addition, we want to provide a system that allows process control strategies to be developed and tested in a safe environment isolated from the plant operations. Dynamic, real-time response of the process models is much more important to meet these goals than steady-state modeling accuracy.

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