Application of Digital Engineering and MBSE Methodology To De-Risk Component Design

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Motivation for Transitioning to a Digital Environment

Initiatives

1. Transition to a full digital engineering environment to increase first-time quality, productivity, efficiency, and achieve better / faster decisions
2. Create a program-wide integrated digital enterprise
3. Create a strong digital culture and a digitally skilled workforce committed to integrating digital tools and technology into all aspects of its operation

DoD Instruction 5000.97

Digital Engineering

Motivation

Digital Enterprise Components

- Agile
- Model-Based
- Data-Centric
- Integrate Supporting Systems
- Digital culture

Benefits

- Improve quality of work
- More efficient processes
- Optimization
- Enhance knowledge management
- Better collaboration
- Positive employee experience

Goals

- Support the Navy
- Achieve 10-1-1*
- Attract and Retain Talent for NNPP**

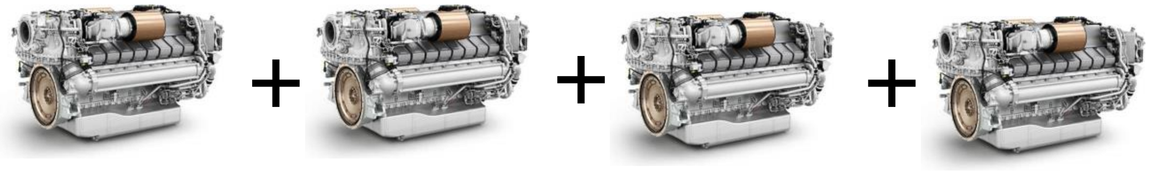
(*) **10-1-1:**

- 10 years or less from concept to field
- 1 year or less to return ships from MRO to active duty
- 1 month or less to respond to field issues

(**) **Naval Nuclear Propulsion Program**

Motivation for Designing a new Heat Exchanger (HTX)

Postulated Scenario: The owner of a large and expensive **luxury yacht** is considering replacing the existing diesel-powered marine propulsion system



with a new proprietary propulsion system that will utilize one or more high-pressure/high-temperature liquid-to-liquid HTXs to transfer thermal energy to a propulsion system **requiring at least 2 MWth per HTX** to generate the necessary horsepower.

The currently available off-the-shelf (OTS) shell-and-tube HTX is inadequate for the job as it cannot provide more than 1 MWth.

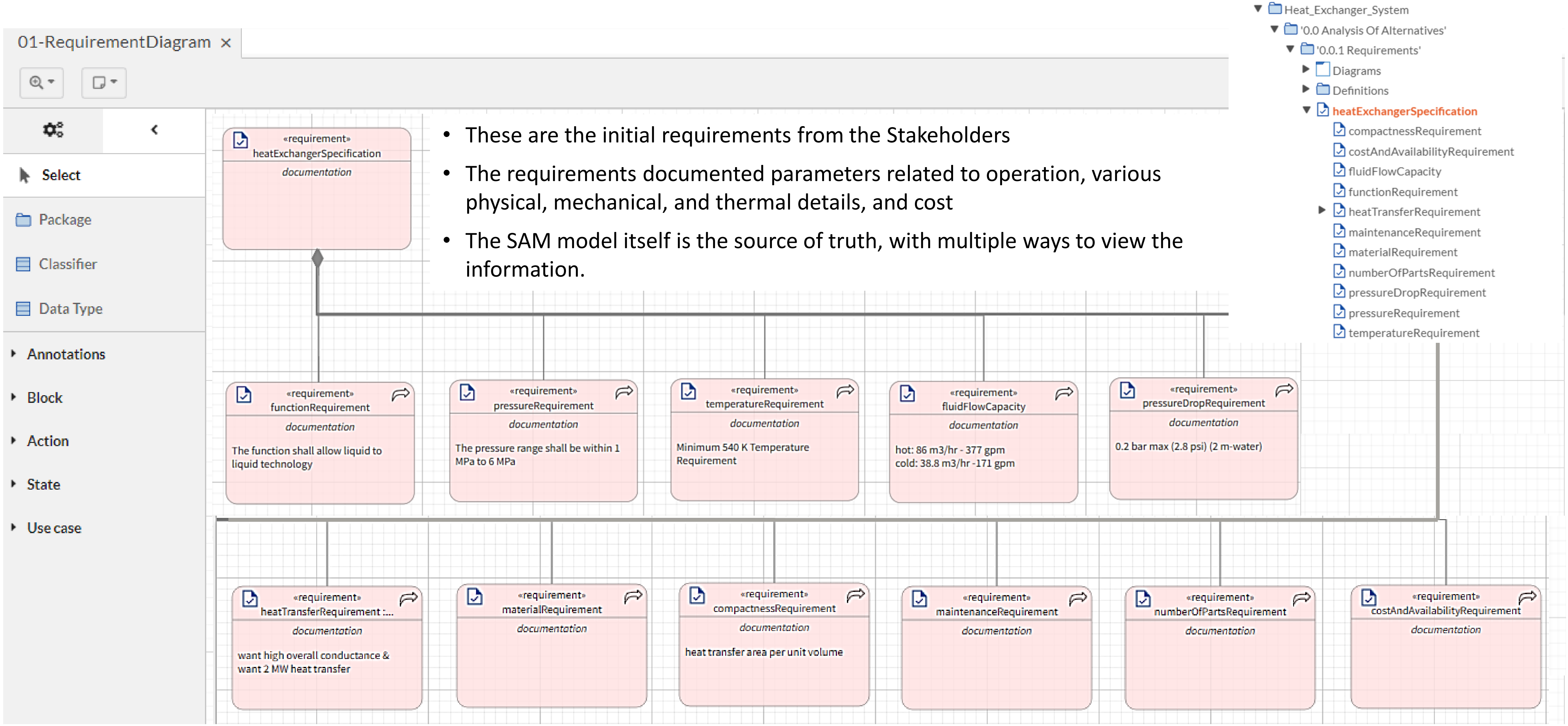
The owner of the yacht provided all specifications and requirements related to operation, size, cost, etc of the desired HTX.

The team must now **start from scratch** the process of creating **the best new HTX design** that meets these requirements

Digital Engineering & Model-Based System Engineering (MBSE)

Stakeholder Requirements Documented in the Ansys System Architecture Modeler (SAM)

- These are the initial requirements from the Stakeholders
- The requirements documented parameters related to operation, various physical, mechanical, and thermal details, and cost
- The SAM model itself is the source of truth, with multiple ways to view the information.



Ansys NAVAL NUCLEAR LABORATORY

Analysis of Alternatives to Determine the Best Heat Exchanger Type

Other heat exchanger types were considered for the 2 MW System Requirement. The choice of heat exchanger type was made using an **Analysis of Alternatives**

The **shell and tube heat exchanger type** was chosen over the alternative types: as the optimal choice considering the System Requirements

	A	B	C	D	E	F	G	H	I	J	K	L	M
1		System Requirement	Weighting factor	Shell& Tube		Plate & Frame		Spiral		Brazed Plate		TPMS	
2	Factor			Notes	Rating	Notes	Rating	Notes	Rating	Notes	Rating	Notes	Rating
3	Function	liquid-liquid	5	Good	3	Good	3	Good	3	Good	3	Good	3
4	Pressure Limits	1 Mpa - 6MPa	5	300 bar (shell). 1400 bar (tube)	3	25 bar with some models up to 40 bar	1	100 bar	3	16 bar (1.6 Mpa)	1		3
5	Temperature Limits	400 K to 540 K	5	upto 1350 K	3	Limited to 450 K due to concerns with gasket material sensitivty to temperature	1	upto 573 K	3	only upto 473 K	1		2
6	Fluid Flow Capacity	hot: 86 m3/hr - 377 gpm											
7		cold: 38.8 m3/hr -171 gpm	5	Capable	3		2		2	Limited in size	2	Limited in size by AM printing equipment	2
8	Pressure Drop	0.2 bar max (2.8 psi) (2 m-water)	4	Manageable	2	Narrow passages lead to large DP	1	wider flow passages than Plate & Frame passages- moderate DP	2	Narrow passages lead to large DP	1	Narrow passages lead to larger DP	2
9	Heat Transfer	want high overall conductance & want 2 MW heat transfer	3	150-1200	2	1000-4000 $W/m^2.K$ but usually not good for large temperature differences	2	High heat transfer efficiency 750-2500 $W/m^2.K$	3	prone to fouling, normally 1 to 10m2 surface area	1	1000-14000	3
10	Material requirements	cost, thermal conductivity, strength, and reactivity with fluid	3	varies with the material selection	2	reduced susceptibility to fouling	2	Subject only to materials of construction	2	Suitable for liquids compatible with braze material	2	Subject only to materials of construction	2
11	compactness (heat transfer area per unit volume)		2	50-100 m2/m3	2	120-660 m2/m3	3		2		2	200-2500 m2/m3	3
12	Footprint	max volume = 45 m3	5	can be configured to fit	3	compact size	3	not as compact as plate & frame	2	compact	3	compact size	3
13	Maintenance	easy to clean	3	easy to clean	3	not the easiest and but prone to leaking	1	easy to clean	3	not easily cleaned	1	difficult to clean	1
14	Number of parts			multiple	2	multiple	2	multiple	2	multiple	2	1 part	3
15	Consistent with today's design	desirable	1	Yes	3	No	1	No	1	No	1	No	1
16	Cost & Availability	<= $50,000	3	Base for cost comparison	2	0.3 the cost of Shell & Tube based on Q/LMTD unit cost - normally the most economical	3	~$600/m2	2		2	much more expensive	1
17													
18	TOTAL RATING				33		25		30		22		29
19	Weighted Rating				117		85		108		77		101

Weighting Factor (scale of 1-5) is an estimate of the relative importance of each system requirement

Rating of a particular HTX in meeting the system requirement Factor (scale of 1-3) is an estimate of how well that particular HTX type meets that system requirement

Weighted Total Rating is based on the Sum (Weight Factor * Rating) for each HTX type

Alternative….Analysis of Alternatives

Factor	System Requirement	Weighting factor	Shell& Tube Notes	Shell& Tube Rating	TPMS Notes	TPMS Rating
Function	liquid-lquid	5	Good	3	Good	3
Pressure Limits	1 Mpa - 6MPa	5	300 bar (shell). 1400 bar (tube)	3		3
Temperature Limits	400 K to 540 K	5	upto 1350 K	3		2
Fluid Flow Capacity	hot: 86 m3/hr - 377 gpm cold: 38.8 m3/hr -171 gpm	5	Capable	3	Limited in size by AM printing equipment	2
Pressure Drop	0.2 bar max (2.8 psi) (2 m-water)	4	Manageable	2	Narrow passages lead to larger DP	2
Heat Transfer	want high overall conductance & want 2 MW heat transfer	3	150-1200	2	1000-14000	3
Material requirements	cost, thermal conductivity, strength, and reactivity with fluid	3	varies with the material selection	2	Subject only to materials of construction	2
compactness (heat transfer area per unit volume)		2	50-100 m2/m3	2	200-2500 m2/m3	3
Footprint	max volume = 45 m3	5	can be configured to fit	3	compact size	3
Maintenance	easy to clean	3	easy to clean	3	difficult to clean	1
Number of parts			multiple	2	1 part	3
Consistent with today's design	desirable	1	Yes	3	No	1
Cost & Availability	<= $50,000	3	Base for cost comparison	2	much more expensive	1
TOTAL RATING				**33**		**29**
Weighted Rating				**117**		**101**

However, the rating system was purposely not representative of Additive Manufacturing as this was not the object of the main analysis (*).

The analysis of alternatives showing how the shell and tube HTX compares to the AM built one using high-performance triply periodic minimal surfaces (TPMS) *using the rating system devised for traditional designs**

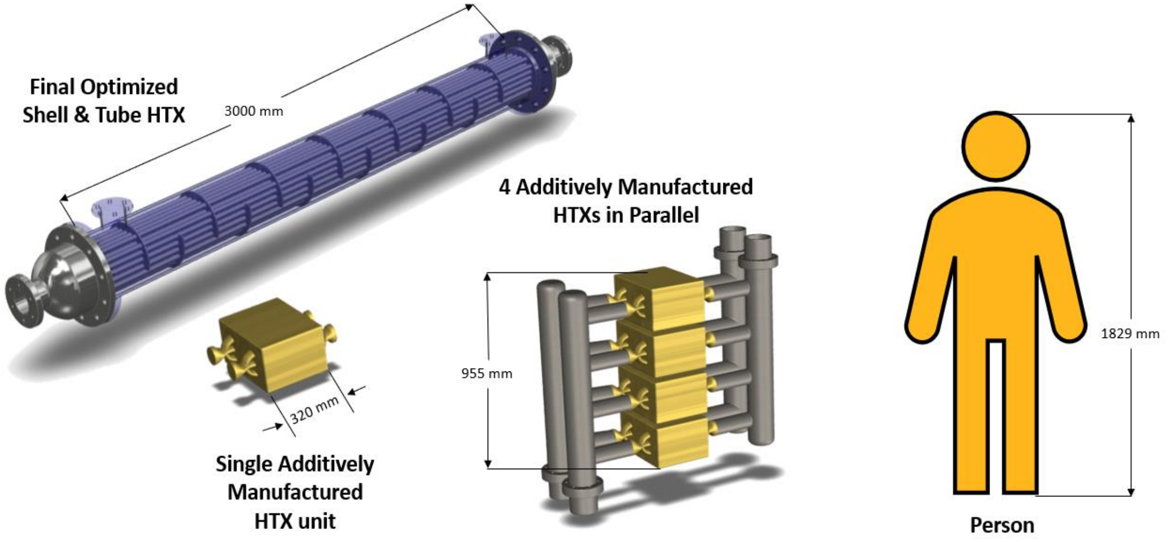
Design Exploration for an Additively Manufactured Heat Exchanger

4 x optimized Heat Exchangers printed from AlSi10Mg connected in parallel can transfer the same amount of heat as the *optimized* shell and tube design but with a *combined* bounding box volume of only **0.15 m³ (13%)**

	AM TPMS HTX	Traditional Shell and Tube Heat Exchanger
Bounding Box Dimensions (mm)	530 x 220 x 320	3640 x 444 x 464
Volume of HTX to transfer 2MW (m^3)	**0.15**	1.14
Volume ratios	**0.13** (total of 4 HTXs)	1 (reference)

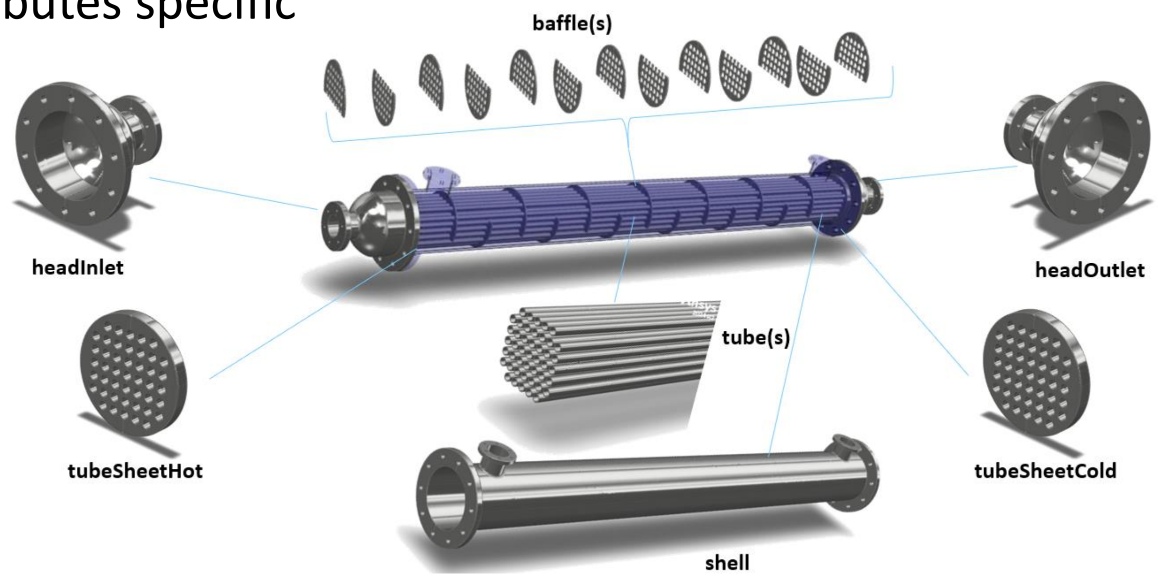
	AM TPMS HTX	Traditional Shell and Tube Heat Exchanger
	AlSi10 Mg	Monel Alloy 400
Heat Transferred per unit volume (MW/m^3)	**21.74**	2.94
Heat transferred per unit surface area (MW/m^2)	**0.69**	0.09

Comparison of Heat Exchanger Sizes for Equivalent Total Heat Transfer



Relative size difference between the traditional shell and tube heat exchanger and the additively manufactured heat exchanger

Shell & Tube HXT: Defining components by assigning attributes specific to each part in SAM



«part def»
ShellAndTubeHX

attributes

areaAvailable : Real
areaRequired : Real
cost : Real
lmtd : Real
overDesign : Real
overSurface : Real
qDividedByLTMDBasedOnQDot : Real
qDot : Real
totalWeight : Real
uRequired : Real
foulingFactor : Real
inletTemperatureHot : Real
outletTemperatureHot : Real
inletTemperatureCold : Real
outletTemperatureCold : Real
massFlowRateHot : Real
massFlowRateCold : Real
fluidPressureHot : Real
fluidPressureCold : Real
maxStress : Real = 1
maxDeformation : Real
maxFoulingThickness : Real
uClean : Real
uDirty : Real
solidDensity : Real
fluidDensityHot : Real
fluidViscosityDynamicHot : Real
fluidSpecificHeatHot : Real
fluidThermalConductivityHot : Real
fluidDensityCold : Real
fluidViscosityDynamicCold : Real
fluidSpecificHeatCold : Real
fluidThermalConductivityCold : Real
geometryMass
axialDeformationMaximum

«part def»
Shell

attributes

shellThickness : Integer
bundleShellDiameteralClear : Real
shellSideHeatTransferCoefficient : Real
totalShellSidePressureDrop : Real
shellInsideDiameter : Real
shellOD : Real
shellOuterTubeLimit : Real
shellMaterial : String
shellEquivalentStress : Real
shellMaterialYieldStress : MaterialYieldStress = MaterialYieldStress::Monel-400

«part def»
Tube

attributes

numberOfTubes : Integer
tubeAtCenter : String
tubeLength : Real
tubeInsideDiameter : Real
tubeOutsideDiameter : Real
tubePitchRatio : Real
tubeThickness : Real
tubeSideHeatTransferCoefficient : Real
tubeSidePressureDrop : Real
velocityThroughATube : Real
tubeMaterial : String
tubePitch : Real
numberCenterTubes : String
tubeThicknessInMilimeters : Real
tubeSheetThickness : Real
tubeWallConductivity : Real
tubeEquivalentStress : Real
tubeMaterialYieldStress : MaterialYield...

«part def»
Head

attributes

headMaterial : String
headEquivalentStress : Real
headMaterialYieldStress : MaterialYieldStress = MaterialYieldStress::Monel-400

«part def»
TubeSheet

attributes

tubeSheetThickness : Real
tubeSheetMaterial : String
tubeSheetEquivalentStress : Real
tubeSheetMaterialYieldStress : MaterialYieldStress = MaterialYieldStress::Monel-400

«part def»
Baffle

attributes

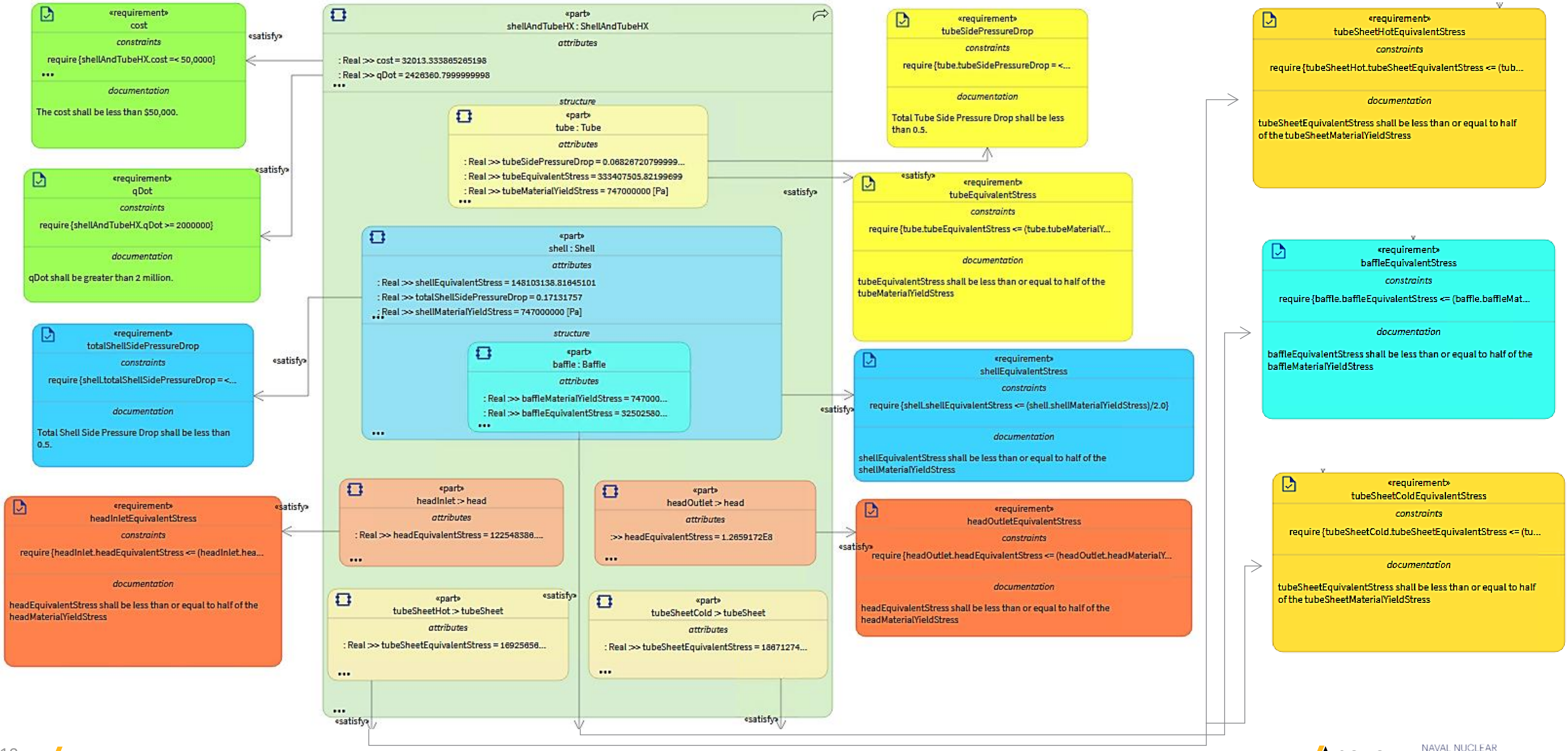
baffleSpacing : Real
segementalBaffleCut : Real
heightOfBaffleCut : Real
numberOfBaffles : Integer
baffleMaterial : String
baffleEquivalentStress : Real
baffleMaterialYieldStress : MaterialYieldStress = MaterialYieldStress::Monel-400
centralBaffleSpace
inletBaffleSpace
outletBaffleSpace

«enumeration def»
MaterialYieldStress

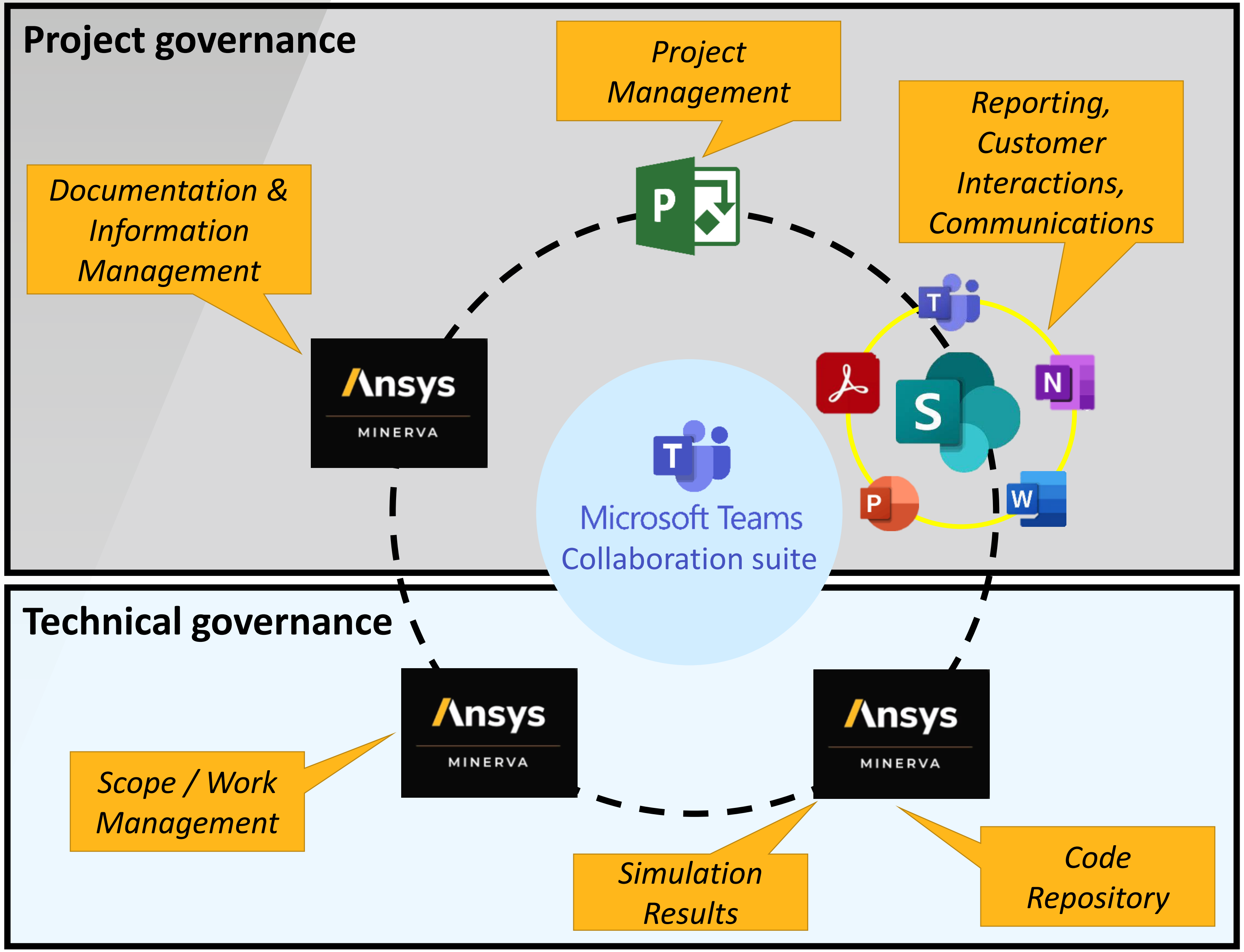
enums

Monel-400 = 747000000 [Pa]
316 Stainless Steel = 250000000 [Pa]
Ti-8-1-1 = 930000000 [Pa]
Inconel 625 = 500000000 [Pa]

System Requirements Displayed in the System Architecture Model



Project execution: Technical Governance



Infrastructure governance

- Establish infrastructure requirements.
- **Holistic approach to meet demand:** consider hardware, software, and operating systems.
- **Establish method to provision** the infrastructure. Provisioning was carried out using **Ansible**.
- **Establish method to** actively manage the operation of the infrastructure. Management using **ServiceNow**.
- Establish a system to manage all simulation process data. Ansys **Minerva** was used as the ASOT for all simulation process data.

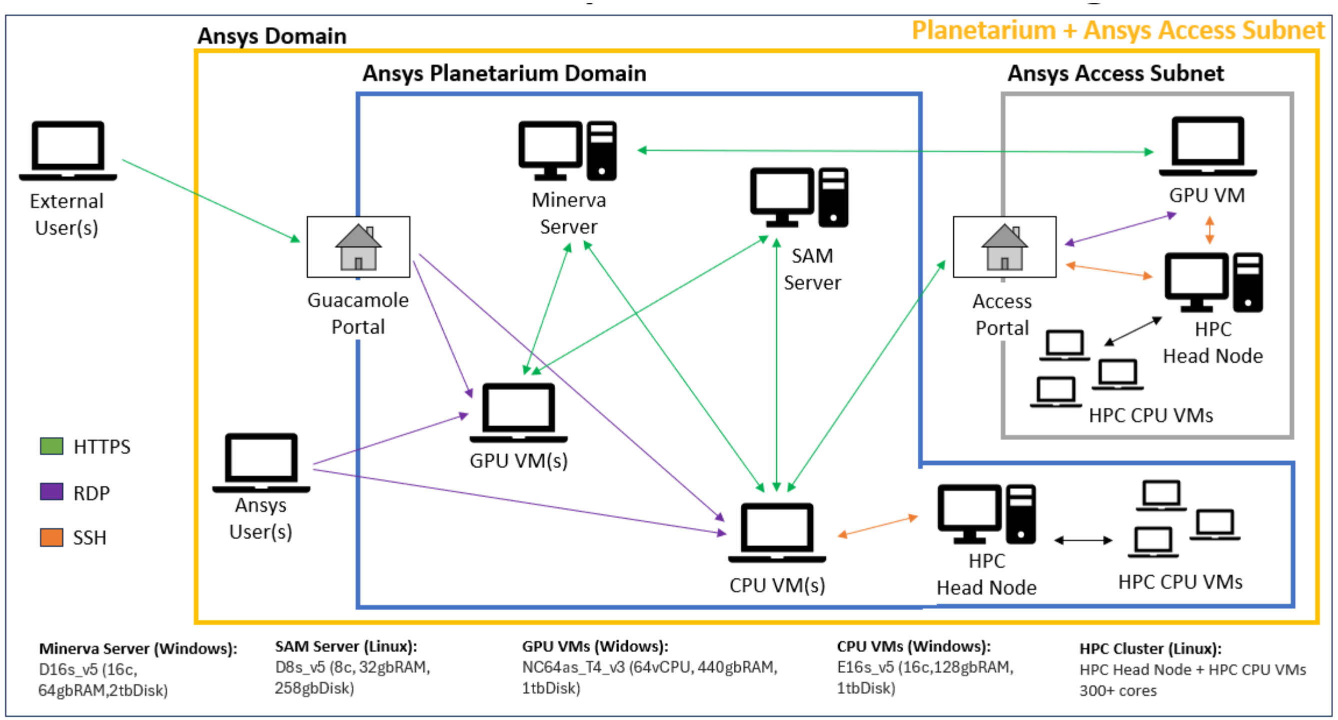
The Ansys Digital Engineering Environment

What is Planetarium?

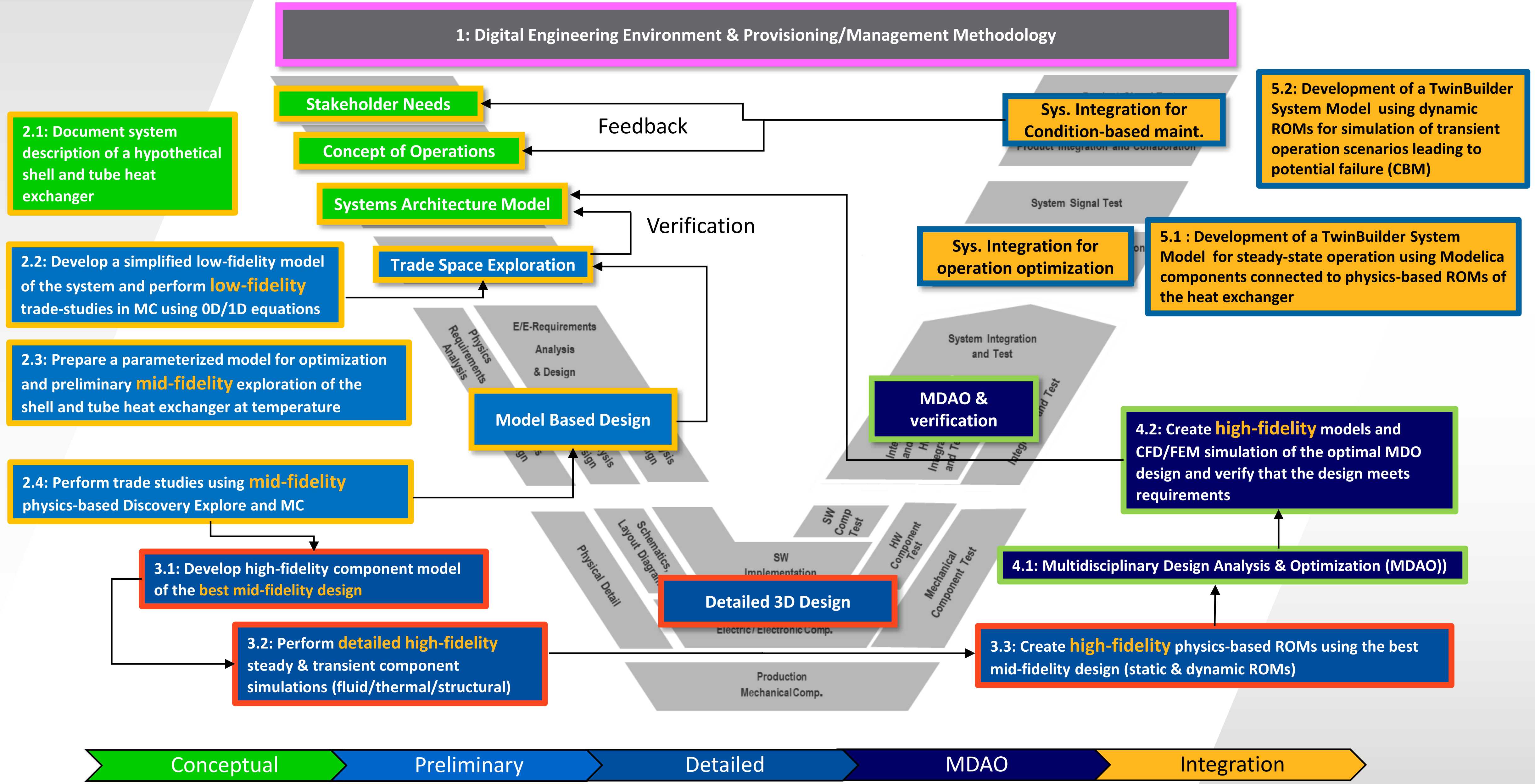
- An Ansys environment where virtual machines (VMs) can be automatically provisioned and managed.
- Software installation is automated based on the user's selection at provisioning.
- Users (internal and external) can access Planetarium via a URL in their browser.
- The underlying cloud infrastructure is through Microsoft Azure.

How is Planetarium Provisioned and Managed?

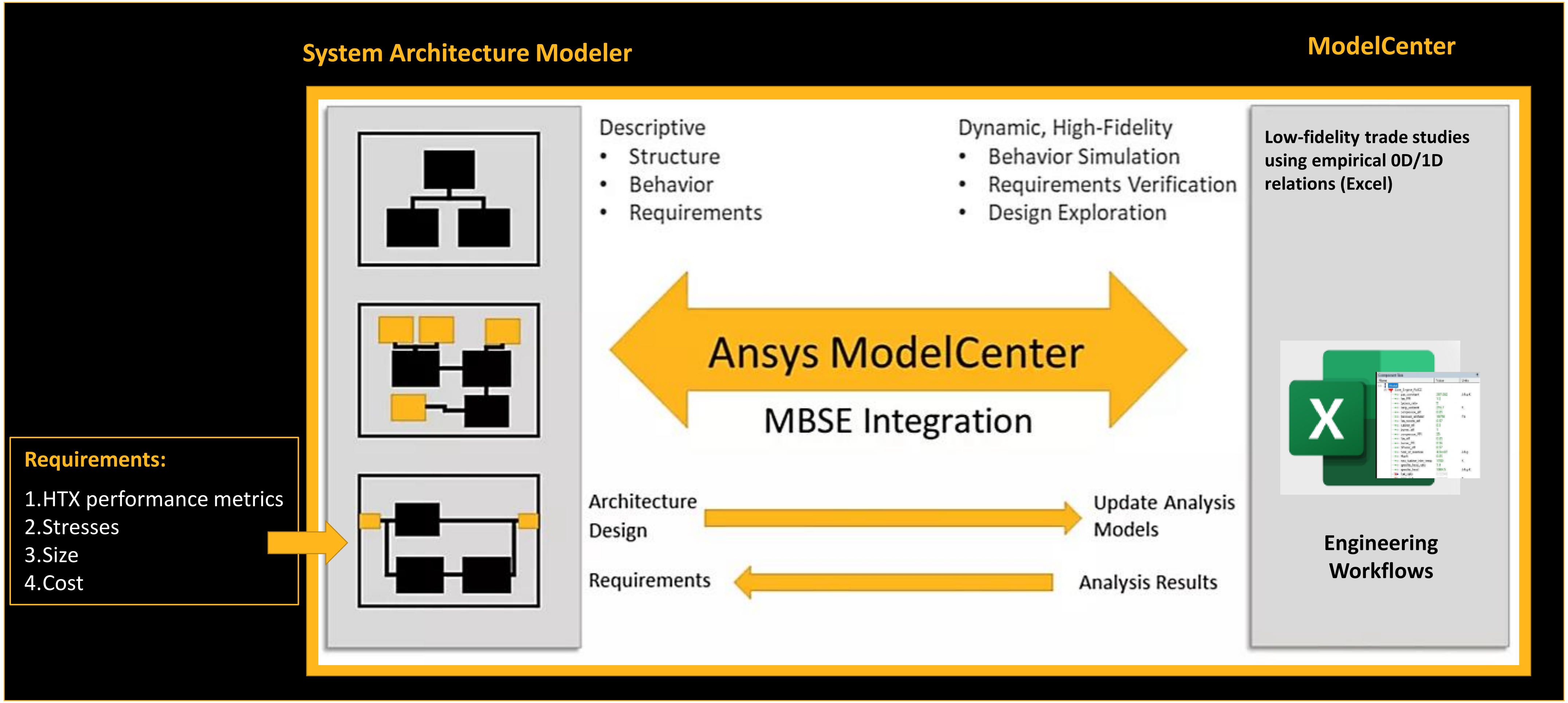
- **Ansible** is an open-source automation tool that automates provisioning, configuration, and management processes.
- **ServiceNow** (S-NOW) is a cloud-based platform that automates and manages business processes, including IT service requests.



Marching through the MBSE Design V

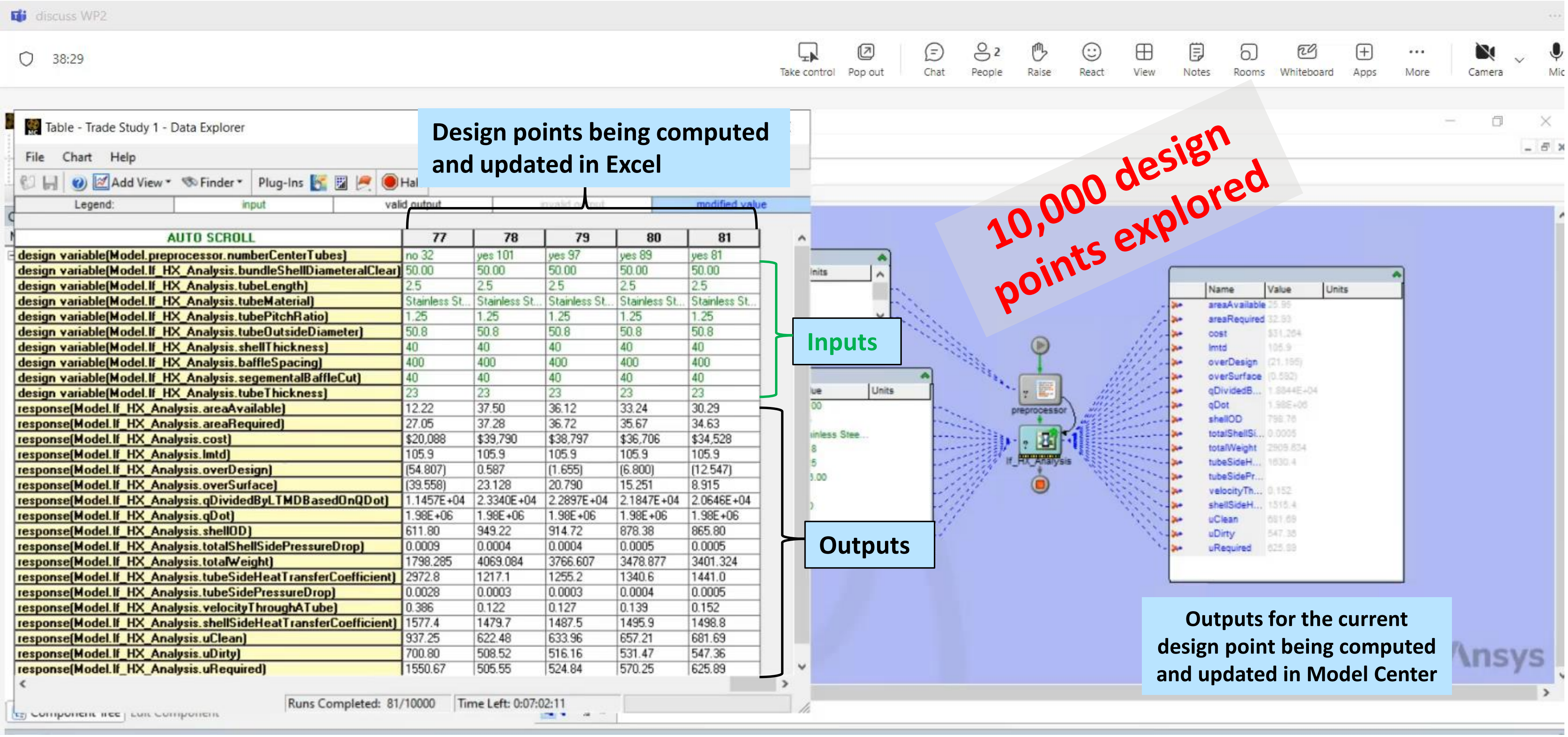


Narrowing of the design space low-fidelity trade studies



Narrowing of the design space low-fidelity trade studies (cont.)

Real-time video of low-fidelity trade study quickly marching through design points



AUTO SCROLL	77	78	79	80	81
design variable(Model.preprocessor.numberCenterTubes)	no 32	yes 101	yes 97	yes 89	yes 81
design variable(Model.lf_HX_Analysis.bundleShellDiameteralClear)	50.00	50.00	50.00	50.00	50.00
design variable(Model.lf_HX_Analysis.tubeLength)	2.5	2.5	2.5	2.5	2.5
design variable(Model.lf_HX_Analysis.tubeMaterial)	Stainless St...	Stainless St...	Stainless St...	Stainless St...	Stainless St...
design variable(Model.lf_HX_Analysis.tubePitchRatio)	1.25	1.25	1.25	1.25	1.25
design variable(Model.lf_HX_Analysis.tubeOutsideDiameter)	50.8	50.8	50.8	50.8	50.8
design variable(Model.lf_HX_Analysis.shellThickness)	40	40	40	40	40
design variable(Model.lf_HX_Analysis.baffleSpacing)	400	400	400	400	400
design variable(Model.lf_HX_Analysis.segementalBaffleCut)	40	40	40	40	40
design variable(Model.lf_HX_Analysis.tubeThickness)	23	23	23	23	23
response(Model.lf_HX_Analysis.areaAvailable)	12.22	37.50	36.12	33.24	30.29
response(Model.lf_HX_Analysis.areaRequired)	27.05	37.28	36.72	35.67	34.63
response(Model.lf_HX_Analysis.cost)	$20,088	$39,790	$38,797	$36,706	$34,528
response(Model.lf_HX_Analysis.lmtd)	105.9	105.9	105.9	105.9	105.9
response(Model.lf_HX_Analysis.overDesign)	(54.807)	0.587	(1.655)	(6.800)	(12.547)
response(Model.lf_HX_Analysis.overSurface)	(39.558)	23.128	20.790	15.251	8.915
response(Model.lf_HX_Analysis.qDividedByLTMDBasedOnQDot)	1.1457E+04	2.3340E+04	2.2897E+04	2.1847E+04	2.0646E+04
response(Model.lf_HX_Analysis.qDot)	1.98E+06	1.98E+06	1.98E+06	1.98E+06	1.98E+06
response(Model.lf_HX_Analysis.shellOD)	611.80	949.22	914.72	878.38	865.80
response(Model.lf_HX_Analysis.totalShellSidePressureDrop)	0.0009	0.0004	0.0004	0.0005	0.0005
response(Model.lf_HX_Analysis.totalWeight)	1798.285	4069.084	3766.607	3478.877	3401.324
response(Model.lf_HX_Analysis.tubeSideHeatTransferCoefficient)	2972.8	1217.1	1255.2	1340.6	1441.0
response(Model.lf_HX_Analysis.tubeSidePressureDrop)	0.0028	0.0003	0.0003	0.0004	0.0005
response(Model.lf_HX_Analysis.velocityThroughATube)	0.386	0.122	0.127	0.139	0.152
response(Model.lf_HX_Analysis.shellSideHeatTransferCoefficient)	1577.4	1479.7	1487.5	1495.9	1498.8
response(Model.lf_HX_Analysis.uClean)	937.25	622.48	633.96	657.21	681.69
response(Model.lf_HX_Analysis.uDirty)	700.80	508.52	516.16	531.47	547.36
response(Model.lf_HX_Analysis.uRequired)	1550.67	505.55	524.84	570.25	625.89

Ansys optiSLang Main Capabilities

Ansys / OPTISLANG

Process Integration

Build and Automate Simulation Workflows

OPEN ECOSYSTEM

Connect to Ansys Multiphysics Solvers

SPEOS | LSDYNA | MOTORCAD | AEDT | WORKBENCH | GRANTA | DCS | DISCOVERY | MINERVA | LUMERICAL | CFX | FLUENT | MODELCENTER | ROCKY | ZEMAX

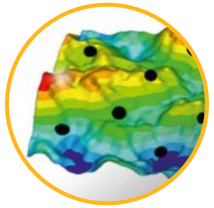
Connect to Third Party Tools

ABAQUS | CATIA | ADAMS | COMSOL | EXCEL | GTPOWER | MATLAB | NASTRAN | PYTHON | SIEMENS NX | FLOEFD | SIMULATIONX | MIDAS | CAESES...

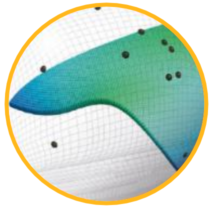
&

Design Optimization

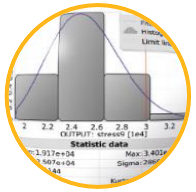
Use Algorithms for Parametric Variation Analysis



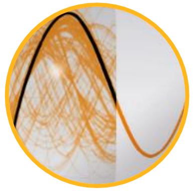
Sensitivity Analysis



Design Optimization



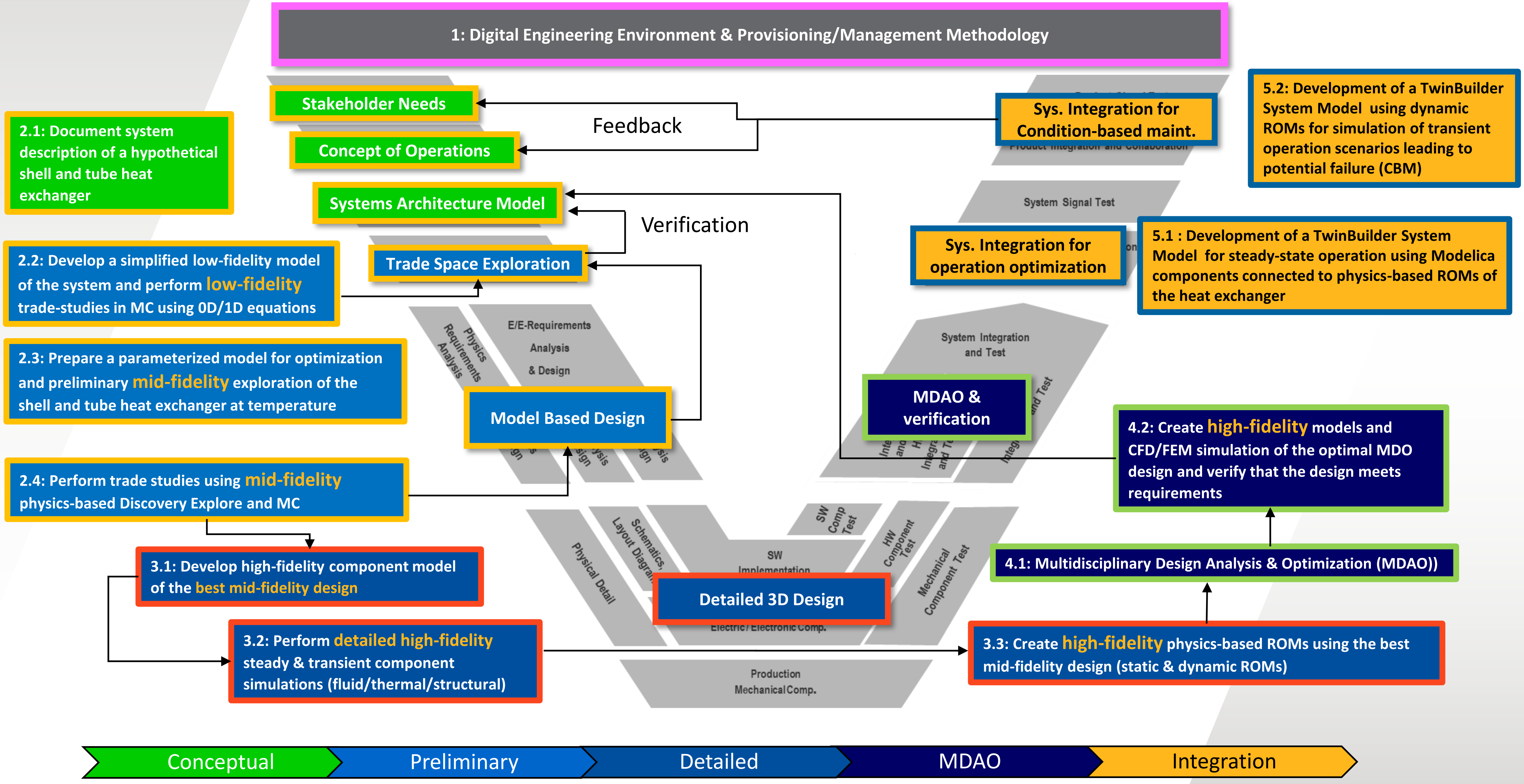
Robustness Evaluation



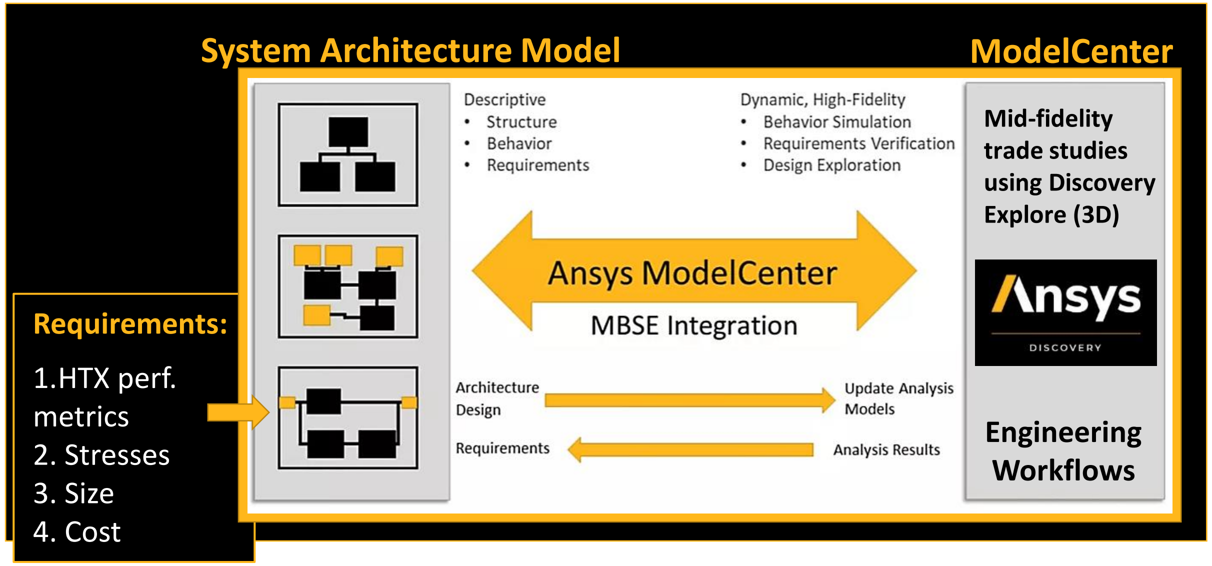
Model Calibration

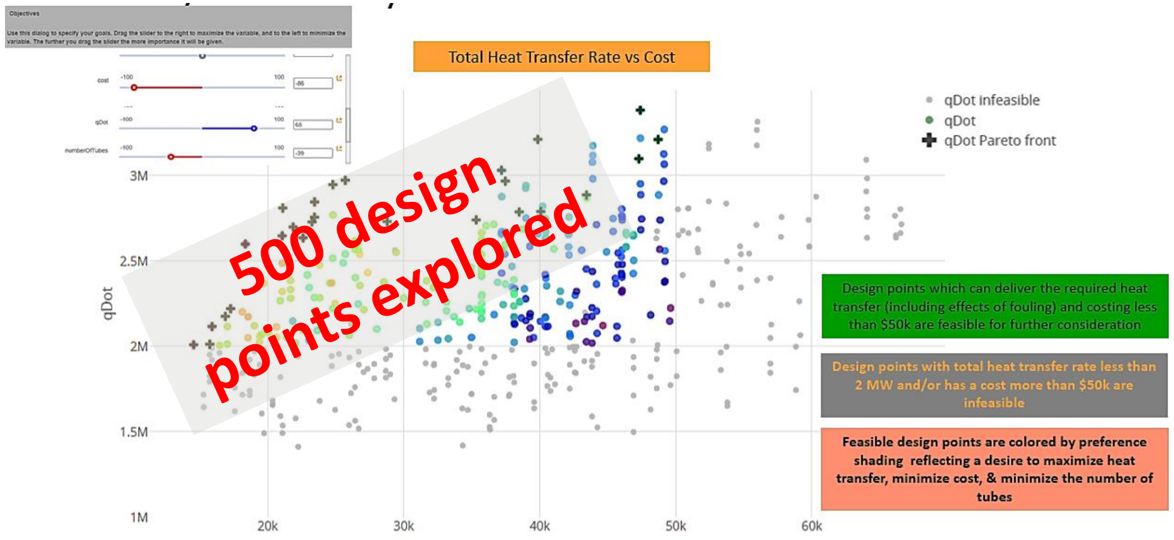
*Directly accessible within Ansys AEDT, Workbench, LS-DYNA, Fluent, ModelCenter

Marching through the MBSE Design V

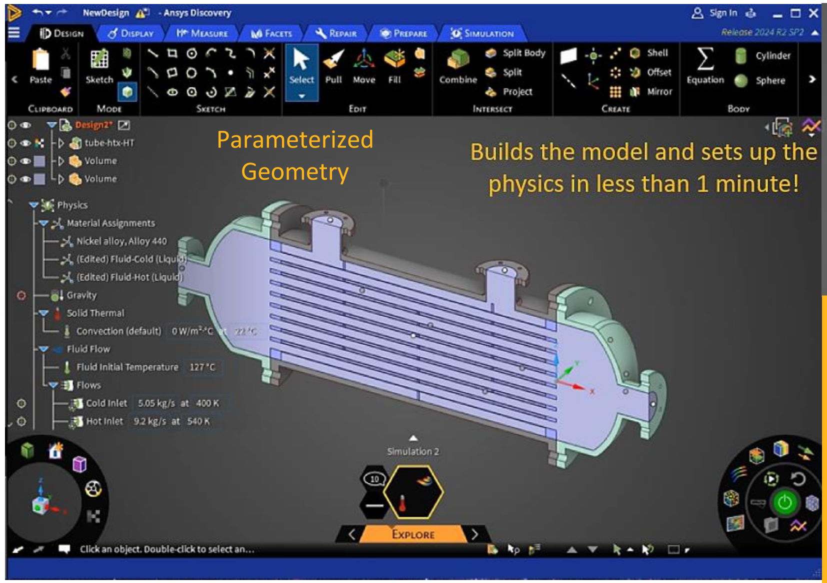


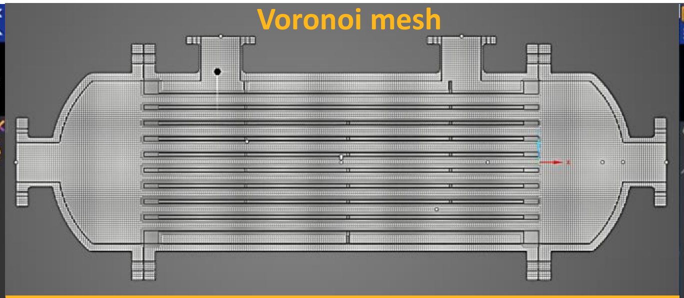
Mid-Fidelity Trade Studies Narrow the Design Space Further



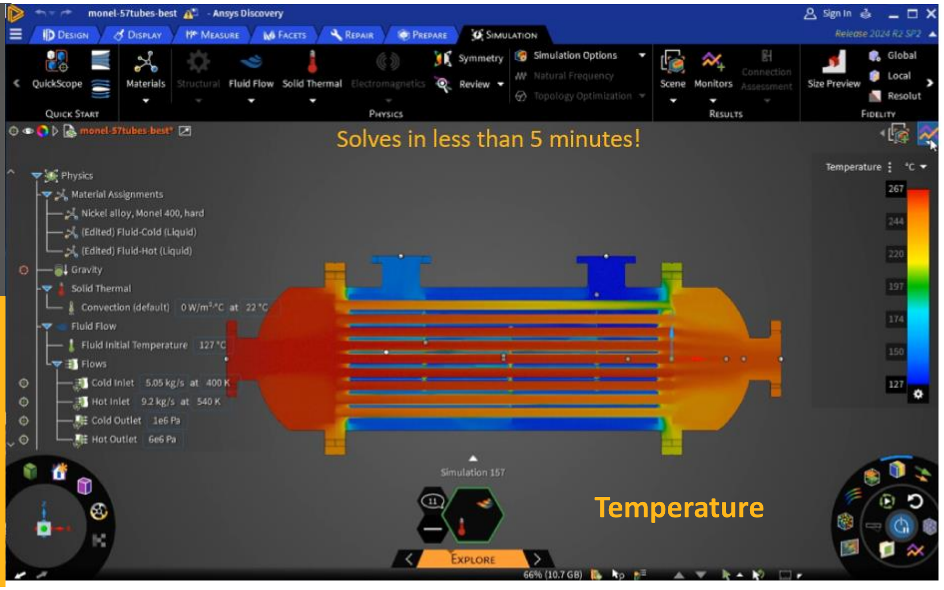


Pareto Front (colored by multiple objectives) indicates the most Promising Designs

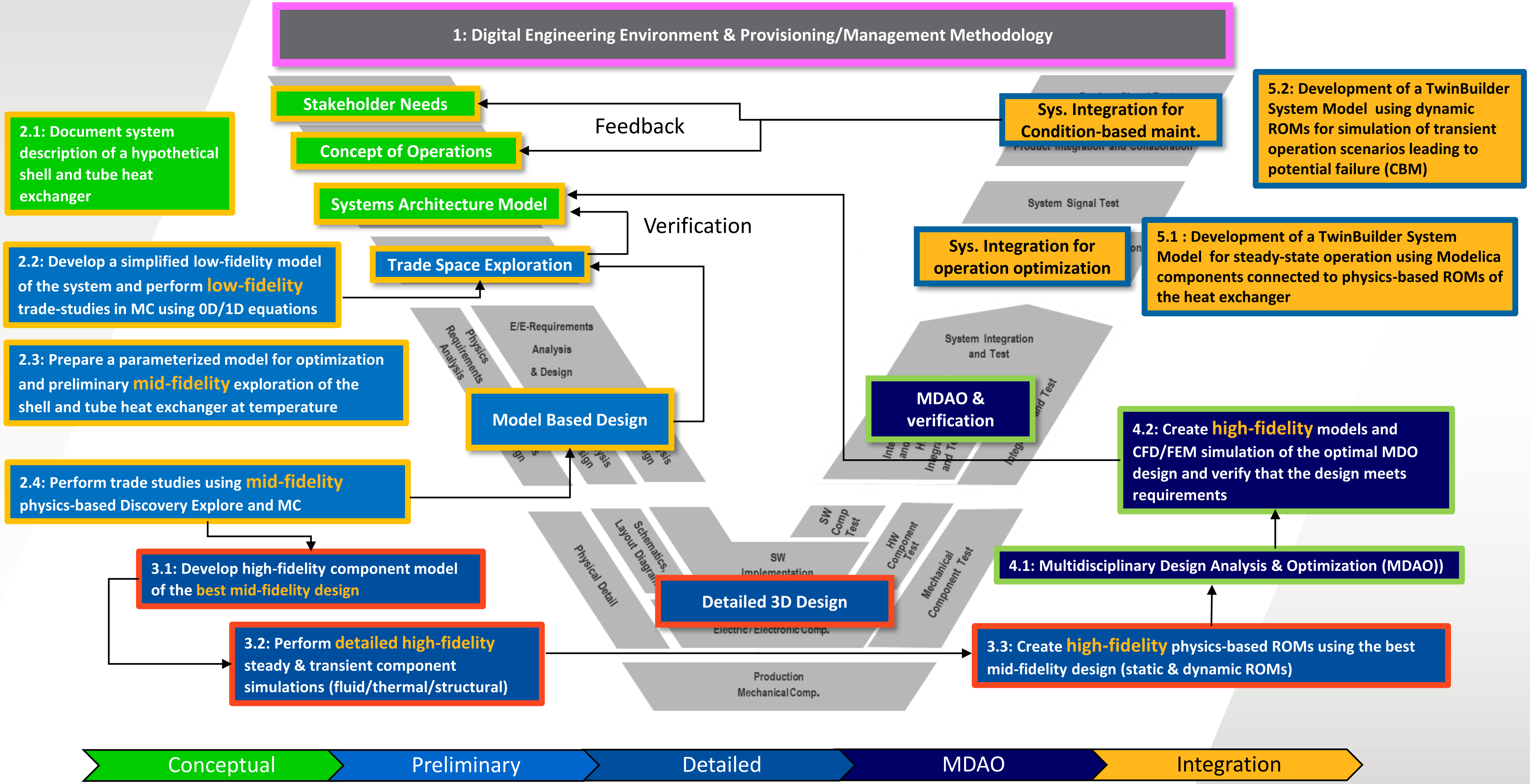




- **Discovery** was used to **rapidly generate geometry** for each new design point using a scripted parameterized geometry and set up the analysis conditions **in less than a minute**
- **Discovery Explore** utilized **GPU solver technology** to solve each design point **in less than 5 minutes**



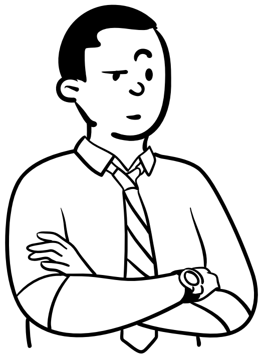
Marching through the MBSE Design V

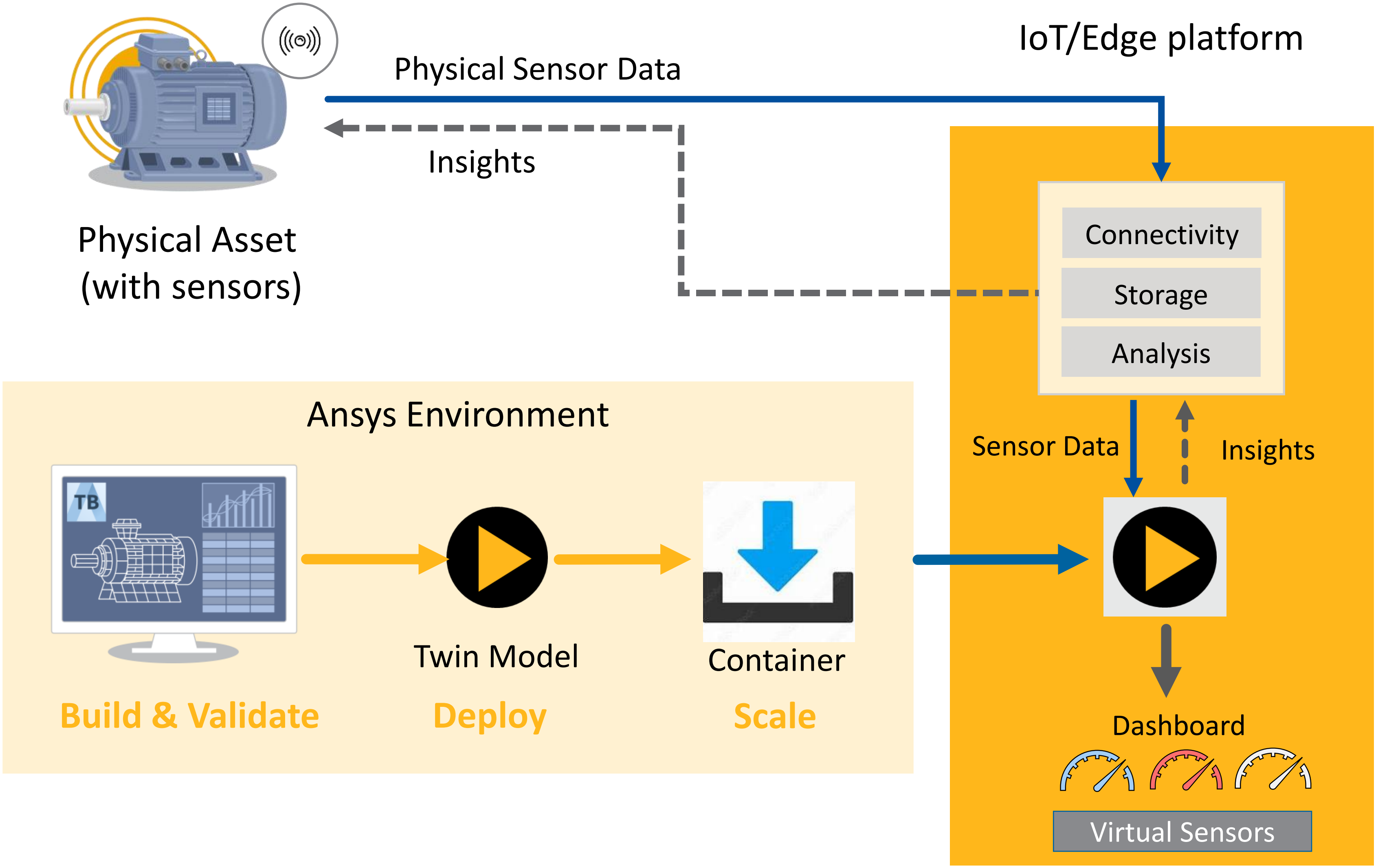


“**Virtual representation** of **real-world entities** and **processes**, **synchronized** at a specified **frequency** and **fidelity**”

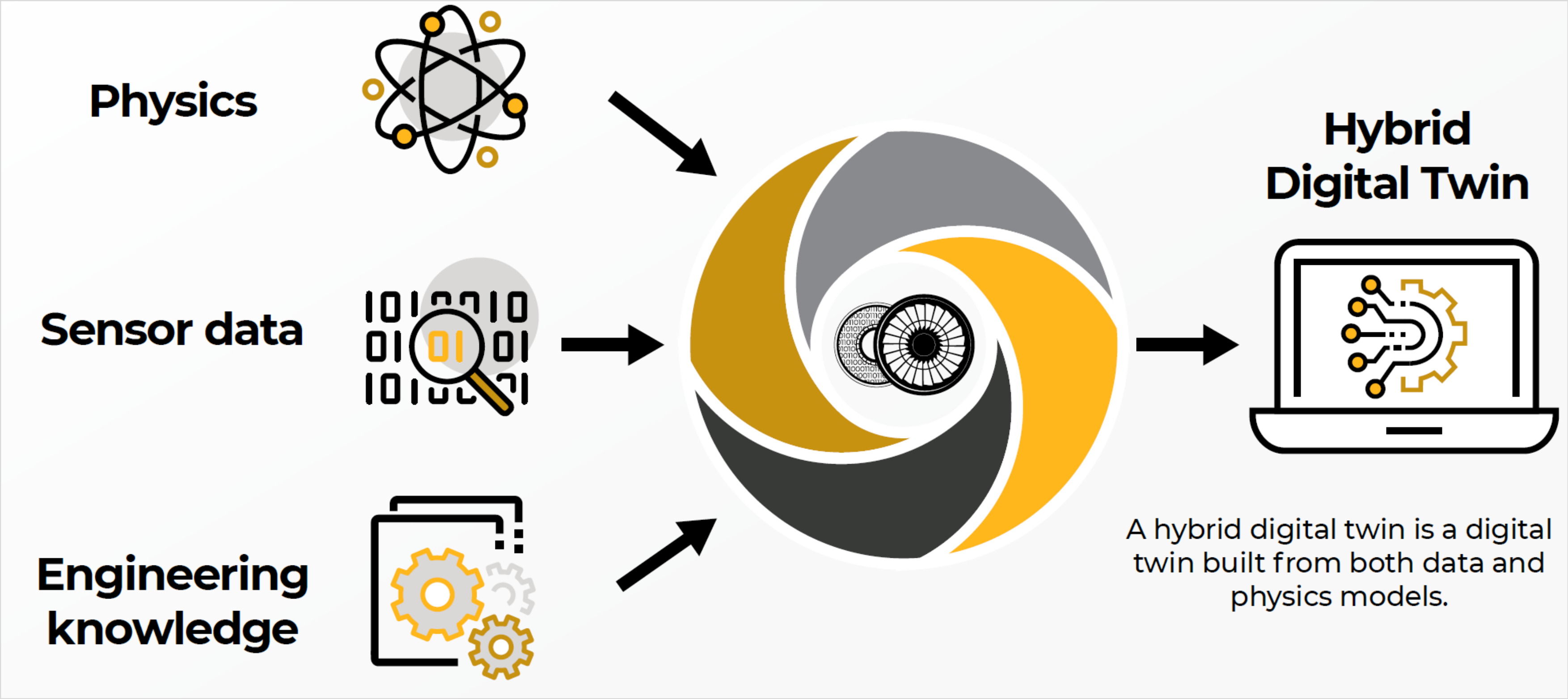
Customer Value:

- Document the past (**data**)
- Provide deeper insights into the present (**operational optimization**)
- Predict and influence future behavior (**condition-based maintenance**)





Hybrid Digital Twins: Leverage Models + Data



A **Hybrid Digital Twin** is a Digital Twin built from both data and physics models

Ansys Twin Builder was used to Build a System Simulation, to Create ROMs and to Explore System Operation

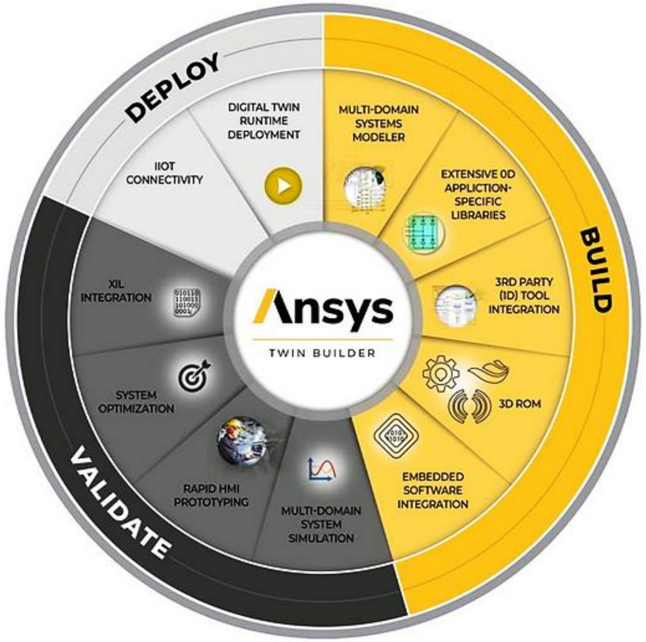
Ansys Twin Builder + TwinAI Hybrid Analytics

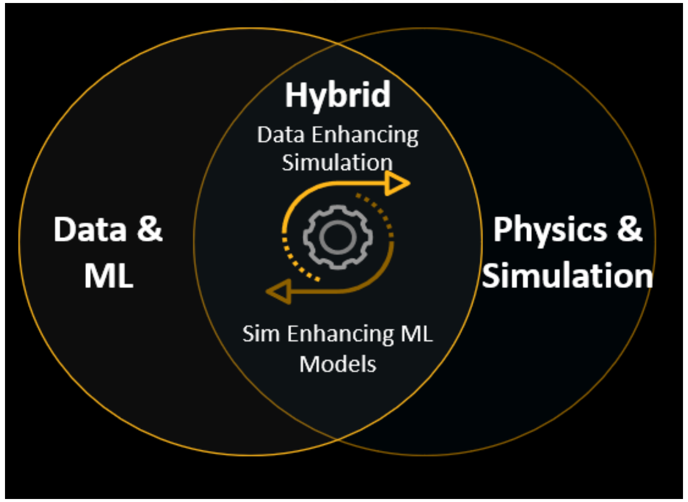
is an open solution that allows one to **create simulation-based digital twins** with the possibility of **augmenting** the DTs **with physical data.**

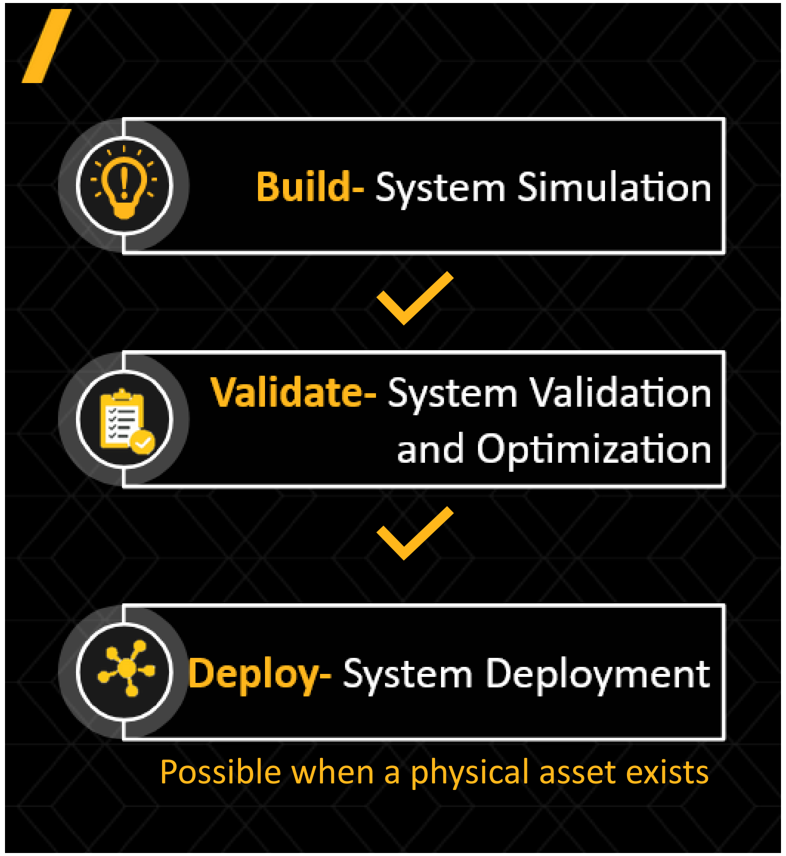
A hybrid analytics-driven digital twin is a trained AI/ML multidomain model that mirrors the behavior of an in-service real asset.

Hybrid digital twins enable:

- System design
- Optimization and industrial asset management
- Predictive maintenance





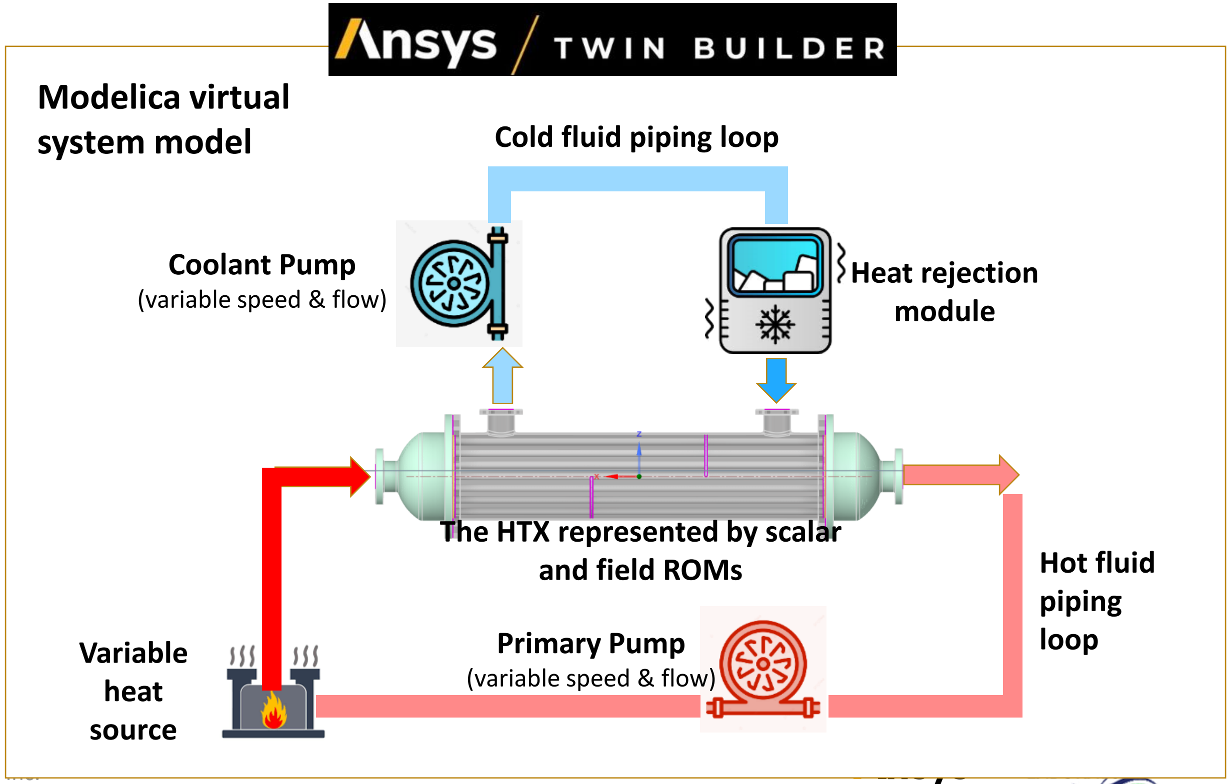


System integration

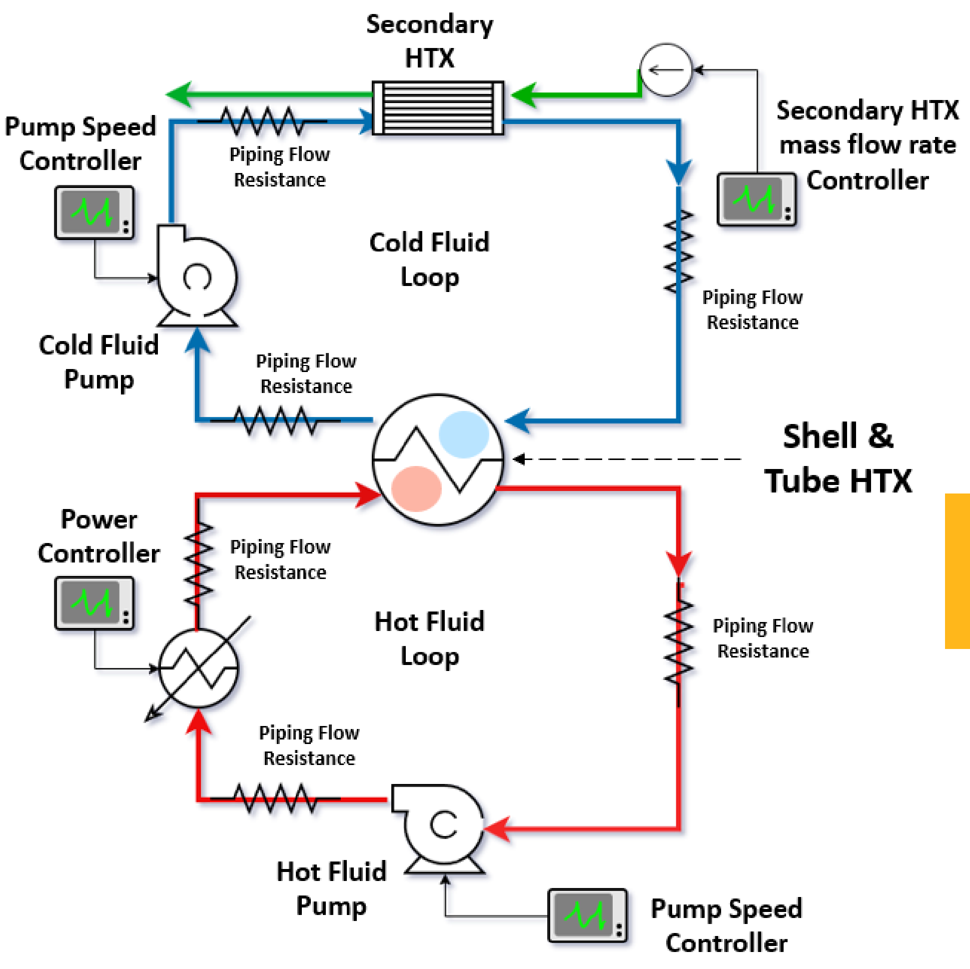
ROMs were integrated into a **virtual system model** using components from the **Modelica system component library** to determine the response of system parameters (flows & temperatures) to what if scenarios for:

1. system operation optimization - using static ROMs in Twin Builder
2. transient operation scenarios leading to potential failure (condition-based maintenance) – using dynamic ROMs in Twin AI

- **Simulated Pump Degradation scenario** (reduced mass flow through the hot fluid loop)
- **Simulated Fouling Degradation scenario** (reduced the heat transfer capability of the shell & tube HTX by 18% over 40,000 seconds)

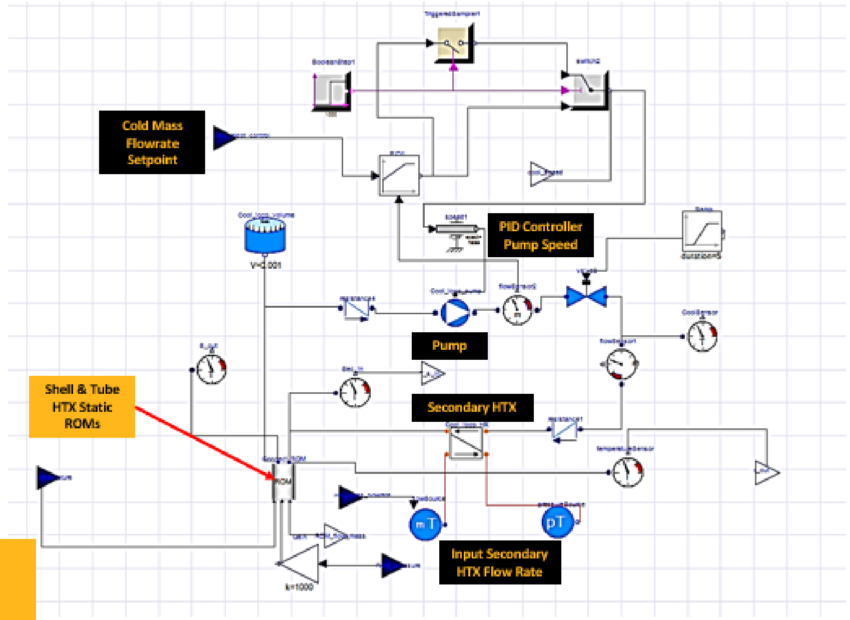


HTX ROMs are part of a System modeled in Twin Builder using native and Modelica components



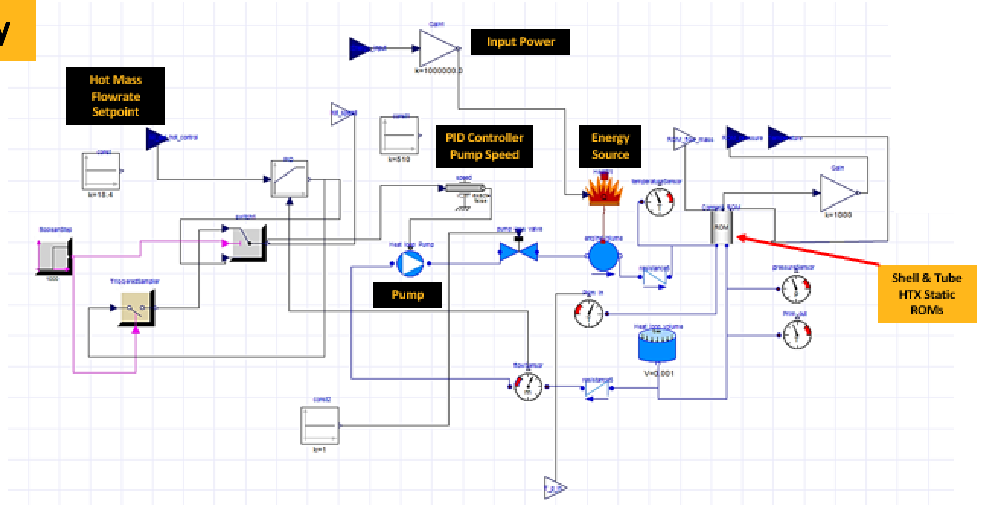
Simplified System Schematic

Cold Fluid Loop Modelica Model

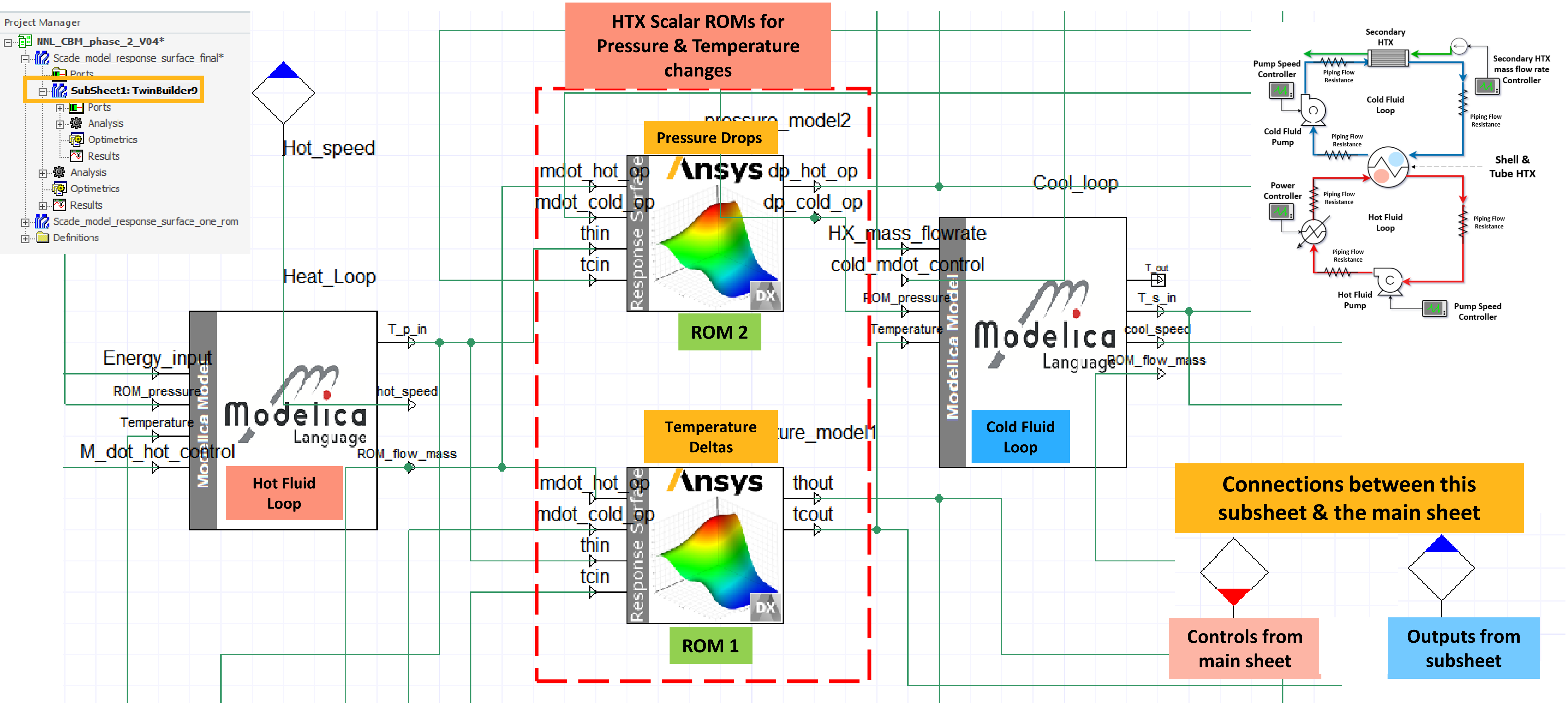


Modelica components were selected from the Modelon Liquid Cooling Library

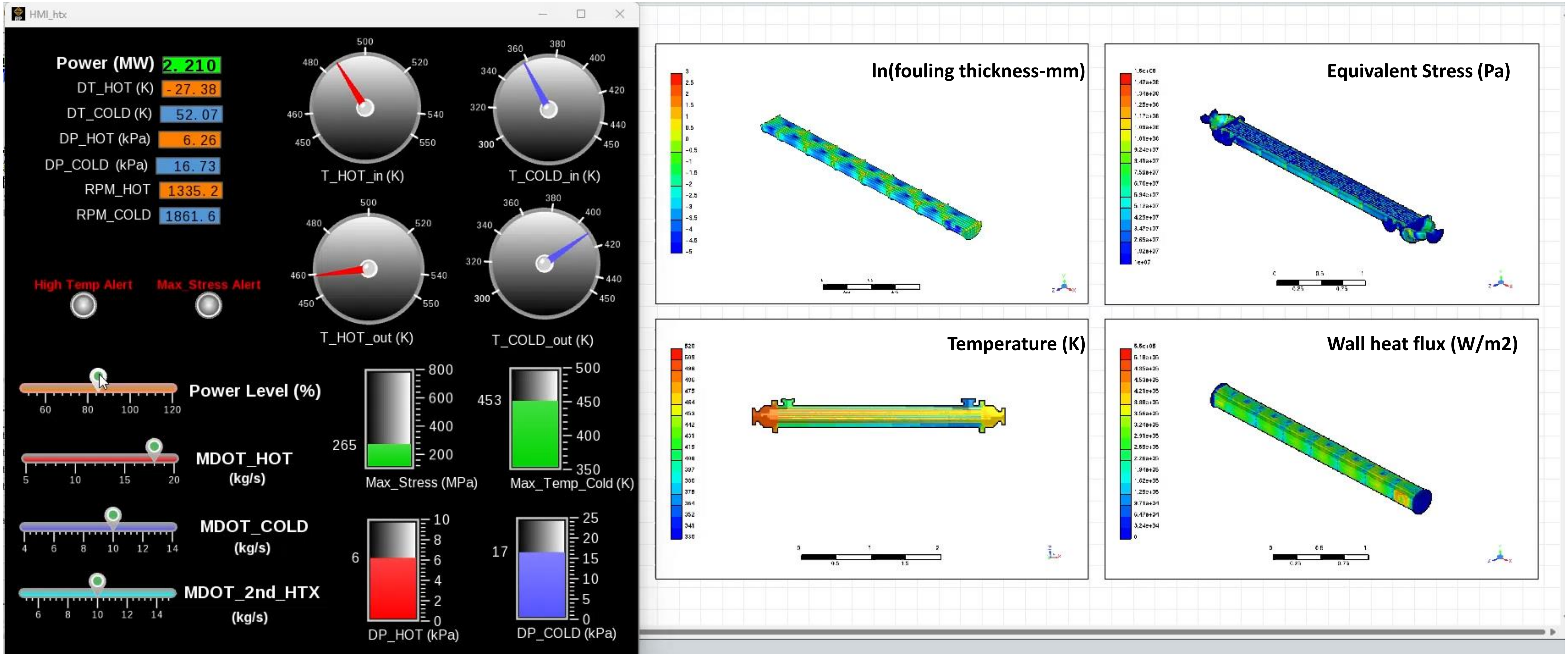
Hot Fluid Loop Modelica Model



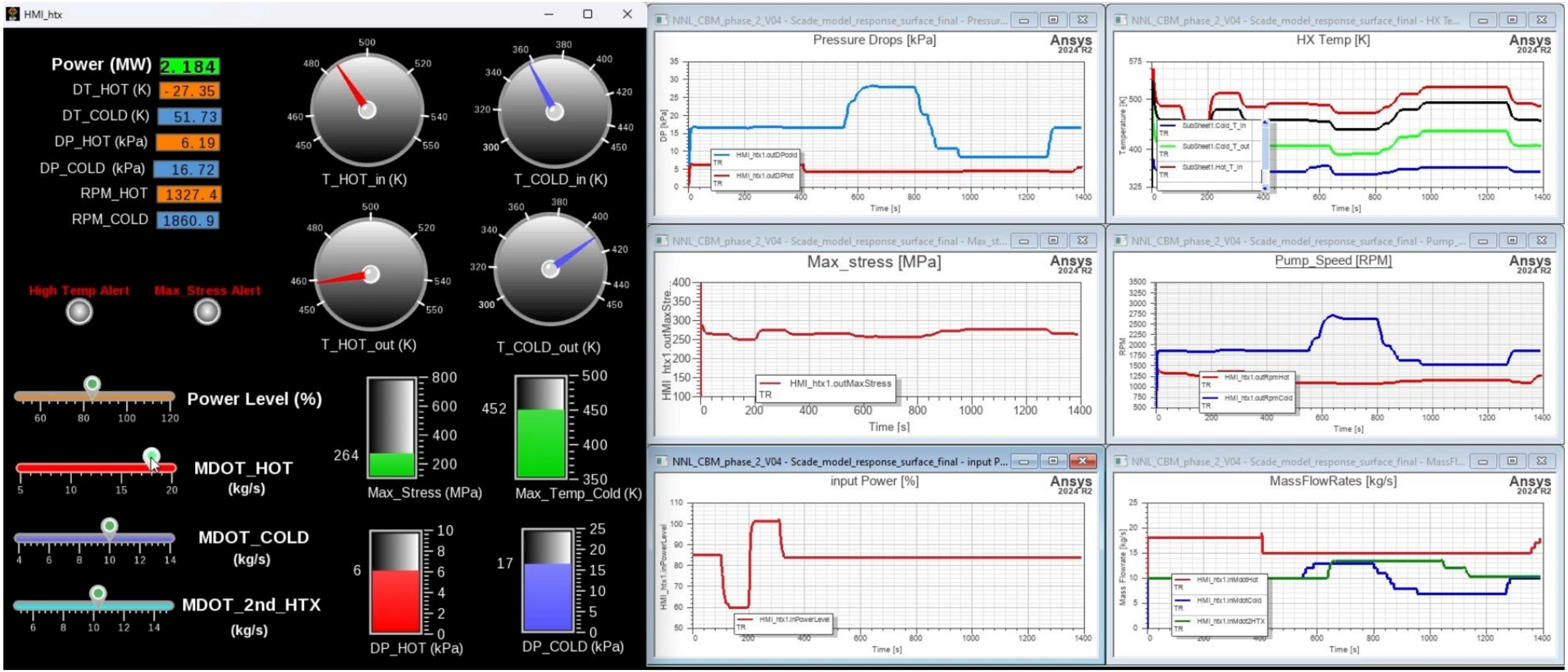
ROMs are connected to Modelica library component models in Twin Builder (sub sheet zoom view)



HMI showing the display, controls, and field ROM imaging



HMI showing the display, controls, and transient virtual sensor information

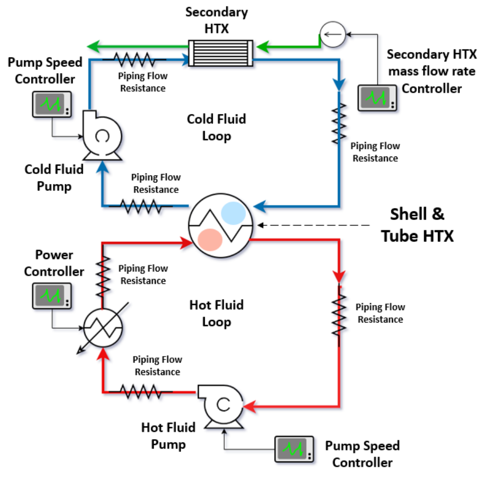


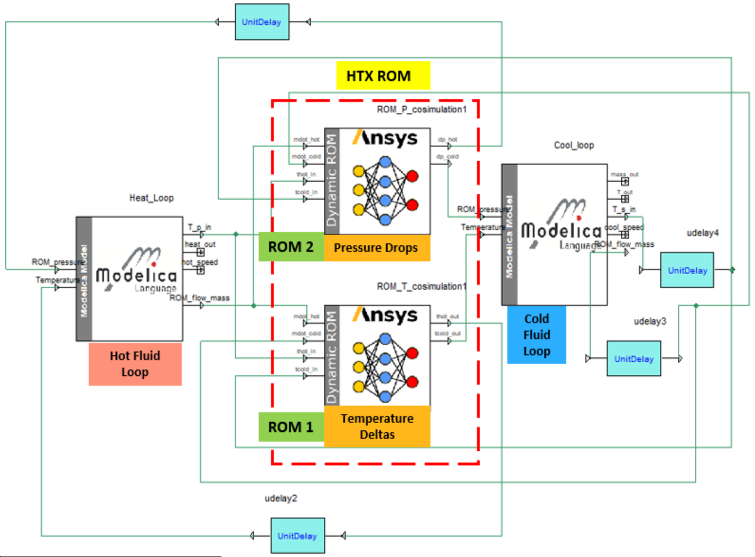
Ansys NAVAL NUCLEAR LABORATORY

Road to Develop a Digital System Model for Condition-Based Maintenance

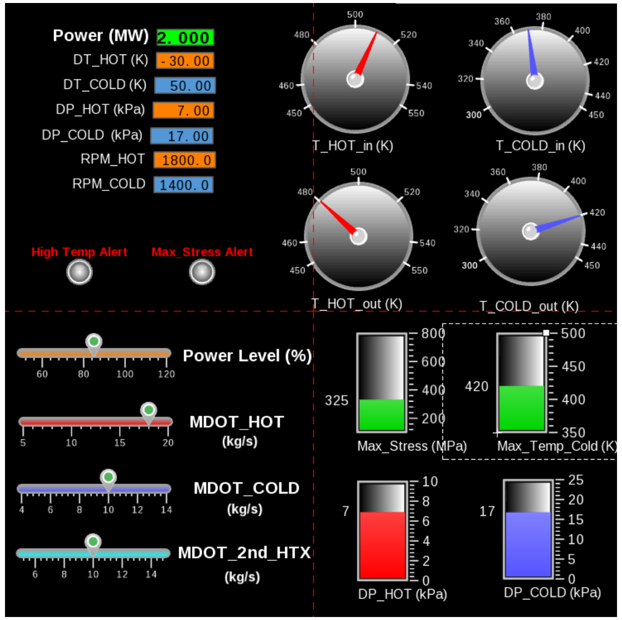
1. **Built a System Model of the HTX System** using **Twin Builder** and **Modelica components**
2. **Developed Static ROMs using high-fidelity multidisciplinary simulations** as (**Static** pressure drops and temperature differences across the shell & tube HTX as well as virtual sensor ROMs for mechanical stress & temperature)
3. **Developed Dynamic ROMs using high-fidelity multidisciplinary simulations (Transient** pressure drops and temperature differences across the shell & tube HTX as well as virtual sensor ROMs for mechanical stress & temperature)
4. **Simulated a CBM Pump Degradation scenario**
5. **Simulated a CBM Fouling Degradation scenario**
6. **Performed What If? for Operational Optimization (Static)**
7. **Performed What If? Pump and Fouling Degradation scenarios for CBM**
8. **Demonstrated potential for improved control strategies**

HTX System Diagram





Interconnection of Modelica fluid loop models with HTX ROMs



Human Machine Interface (HMI) used to set input parameters and report system output parameters