Opportunities for Digital Twins in the Built Environment

A virtual National Academies symposium hosted by:

Board on Mathematical Sciences and Analytics

Board on Infrastructure and the Constructed Environment

Board on Energy and Environmental Systems

Scan here to participate
in Q&A from your phone!

JUNE 13 2024

Expectations for Conduct

We are committed to fostering a professional, respectful, inclusive environment where all participants can participate fully in an atmosphere that is free of harassment and discrimination based on any identity-based factors.

- The National Academies of Sciences, Engineering, and Medicine (NASEM) are committed to the principles of diversity, integrity, civility, and respect in all of our activities.
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BMSA Mission

Provide expertise drawn from a wide range of mathematical sciences to conduct independent and rigorous assessment of science, engineering, medical, defense, and policy issues in the service of national interest.

The Board strives to:

- Provide actionable mathematical advice to policy makers
- Strengthen connections between application areas and mathematics, statistics, and data science
- Support the health of the mathematical sciences ecosystem and a robust educational pipeline
- Increase public awareness of the expanding role of the mathematical sciences

BICE Mission

Advises the executive and legislative branches of government, other governmental and private sector organizations, and the general public on questions of technology, science, and public policy applied to:

- the design, construction, operations, maintenance, security, and evaluation of buildings, facilities, and infrastructure systems;
- the relationship between the constructed and natural environments and their interaction with human activities;
- the effects of natural and manmade hazards on constructed facilities and infrastructure
- the interdependencies of infrastructure systems and the potential for cascading failures

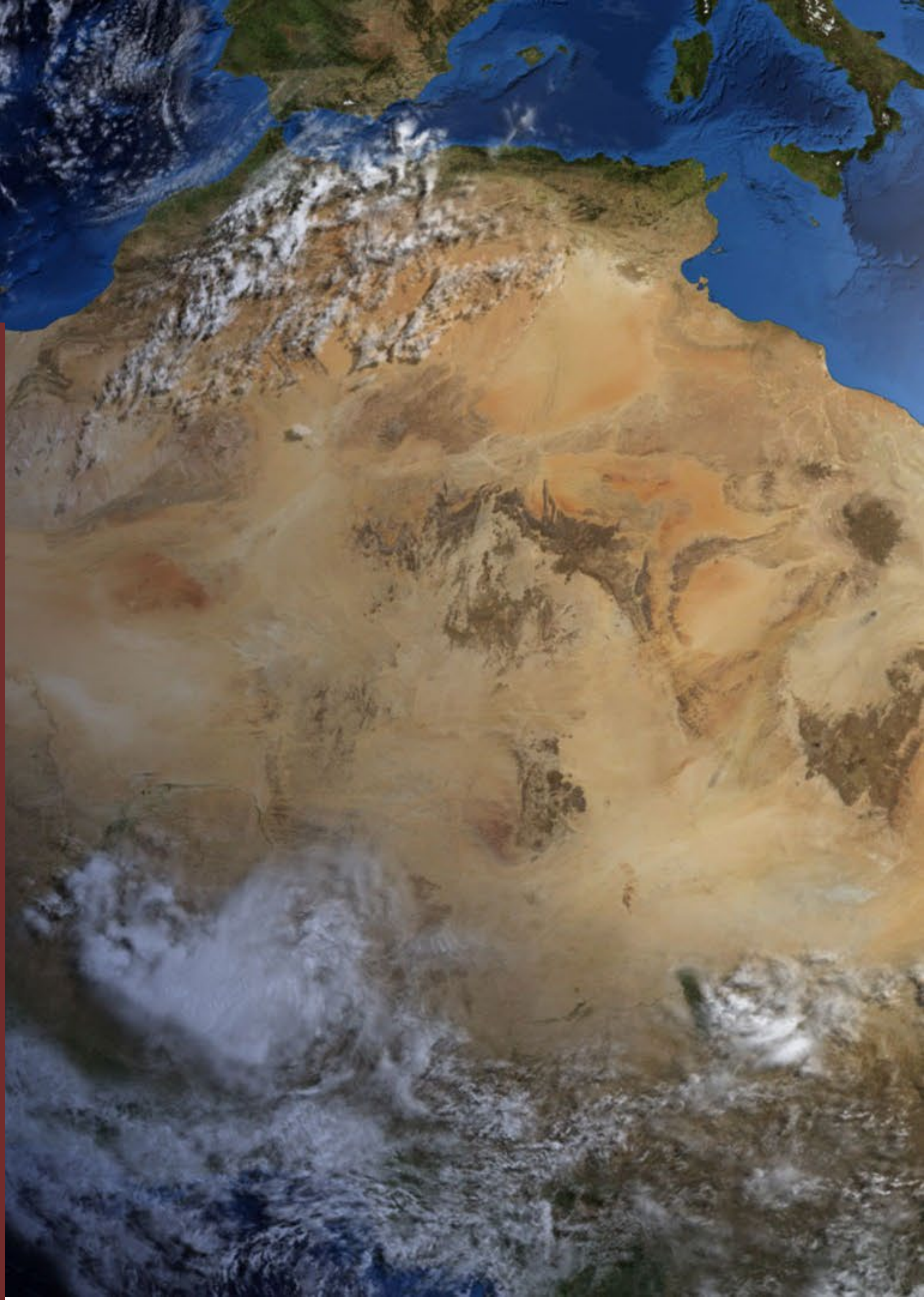
BEES Mission

Bring together experts from across academia, government, non-profit organizations and industry to provide timely and actionable advice on energy policies, regulations, and research. BEES activities advance the discussion on the latest energy technologies, policies, and the societal and environmental implications of energy system changes.

Core themes include:

- Accelerating a Just Transition to Net Zero
- Supporting the Future Electric Power System
- Guiding Vehicle Efficiency Regulations
- Enhancing Innovation in Energy Technologies

NATIONAL ACADEMIES *Sciences Engineering Medicine*



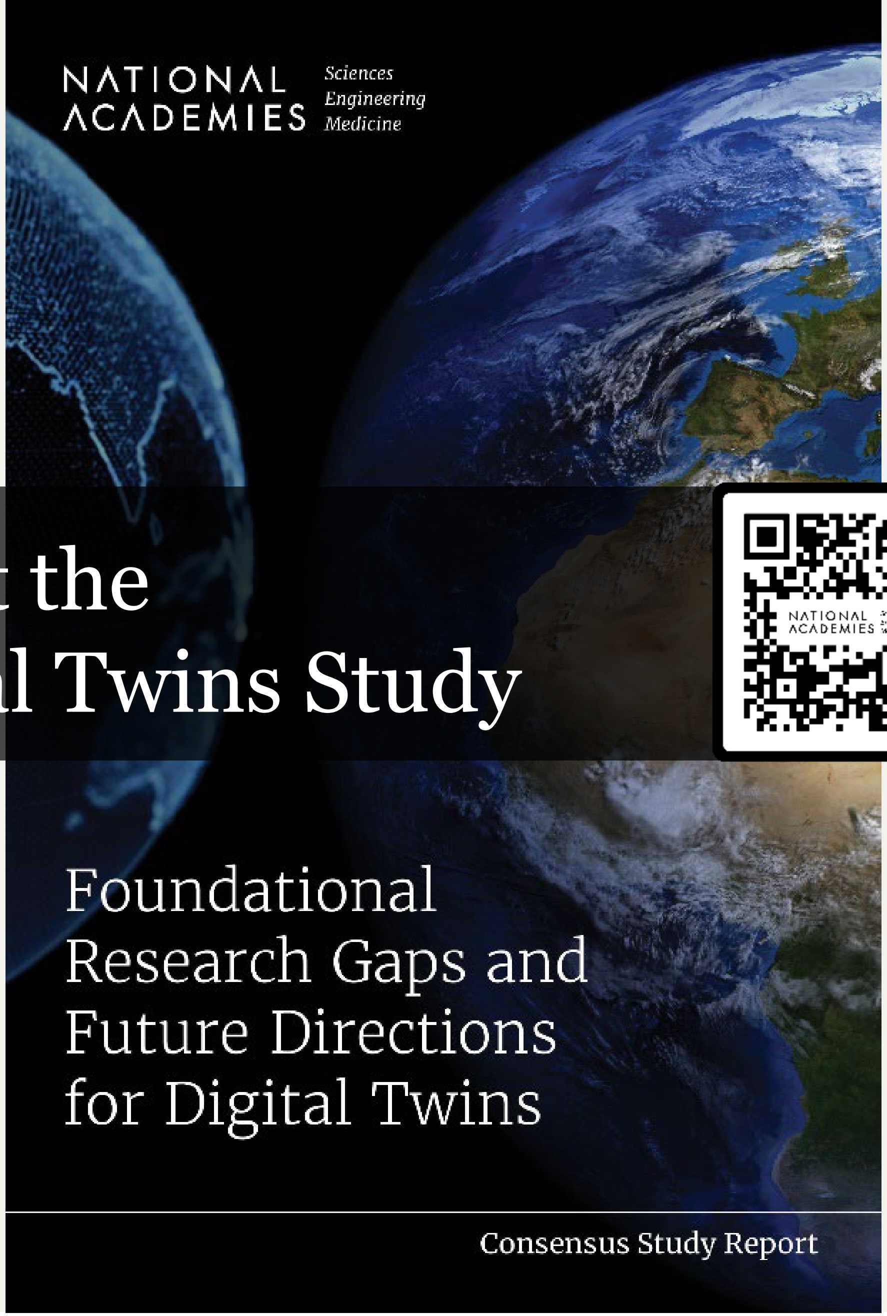
Foundational Research Gaps and Future Directions for Digital Twins

Carolina Cruz-Neira

June 13, 2024

https://www.nationalacademies.org/digital-twins

About the Digital Twins Study



NATIONAL ACADEMIES Sciences Engineering Medicine

Foundational Research Gaps and Future Directions for Digital Twins

Consensus Study Report

Advancing mathematical, statistical, and computational foundations

- How are digital twins defined across different communities?
- Foundational research needs and systemic gaps
- Promising practices across domains and sectors
- Opportunities for translation of best practices across domains
- Use cases for awareness and building confidence
- Key opportunities in research, development, and application

Report Snapshot


NATIONAL ACADEMIES *Sciences Engineering Medicine*

Foundational Research Gaps and Future Directions for Digital Twins

Consensus Study Report

0. Summary
1. Introduction
2. The Digital Twin Landscape
3. Virtual Representation
4. The Physical Counterpart
5. Feedback Flow from Physical to Virtual
6. Feedback Flow from Virtual to Physical
7. Towards Scalable and Sustainable Digital Twins
8. Summary of Findings, Conclusions, and Recommendations

48	22	19	8
Gaps	Findings	Conclusions	Recommendations

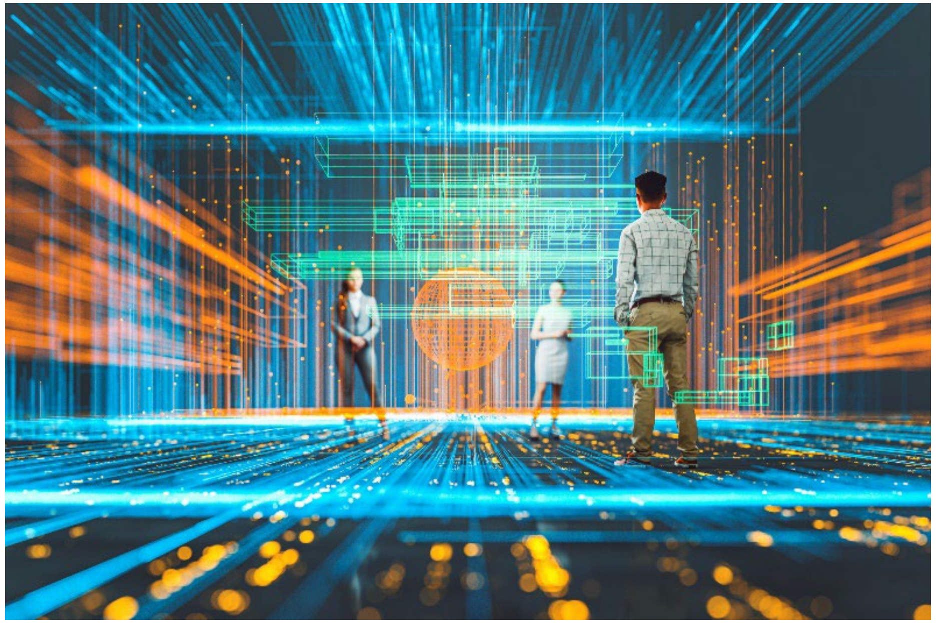
Definition of a Digital Twin

> “*A digital twin is a set of virtual information constructs that mimics the structure, context, and behavior of a natural, engineered, or social system (or system-of-systems), is dynamically updated with data from its physical twin, has a predictive capability, and informs decisions that realize value. The bidirectional interaction between the virtual and the physical is central to the digital twin.*

Committee’s definition builds on a definition from an AIAA and AIA Position Paper (2020)

FOCUSED RESEARCH NEEDS

SYSTEMIC, TRANSLATIONAL & PROGRAMMATIC

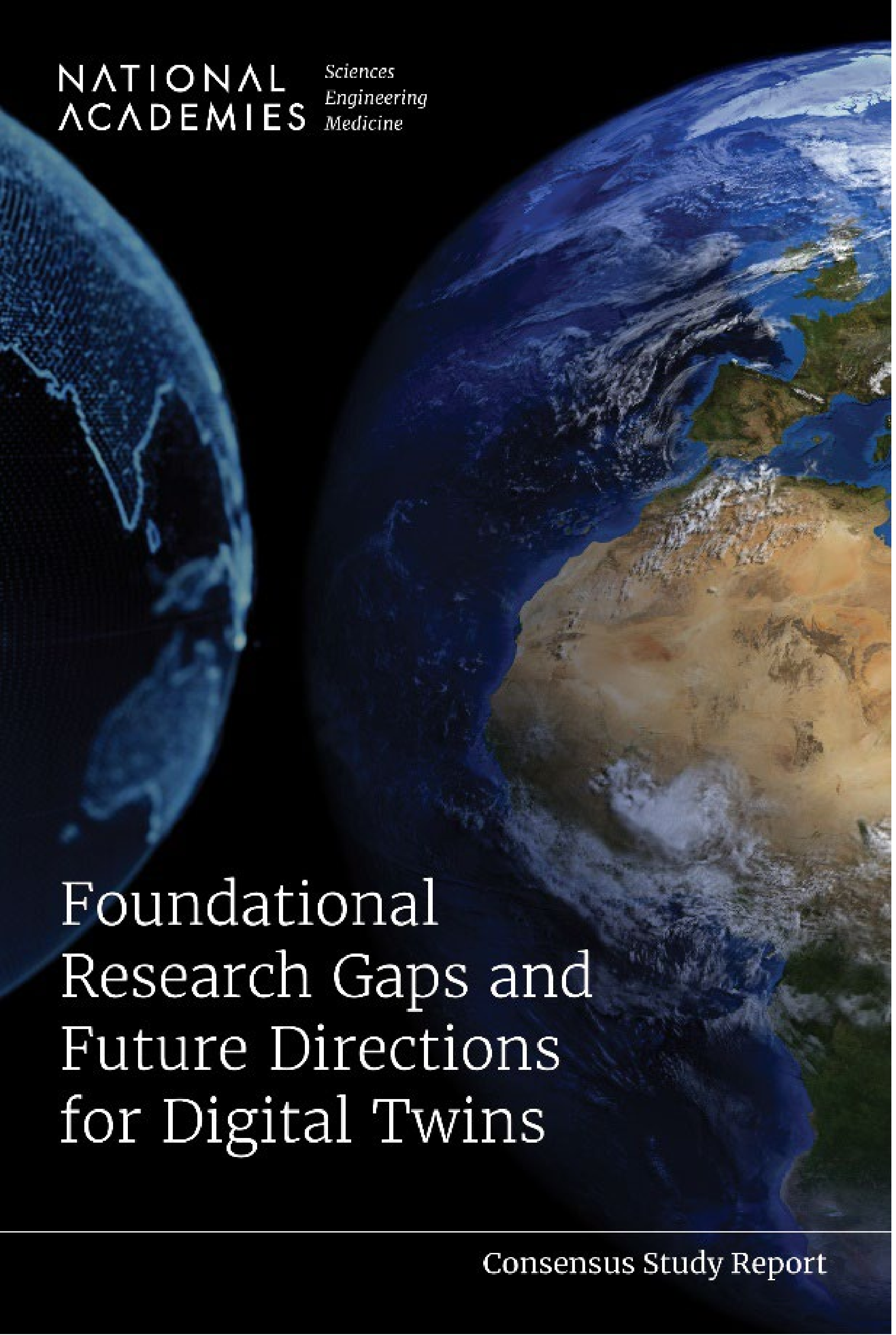


Digital twin sustainability

Translational & collaborative research

Fostering model & data collaborations

Interdisciplinary education



NATIONAL ACADEMIES Sciences Engineering Medicine

Foundational Research Gaps and Future Directions for Digital Twins

Consensus Study Report

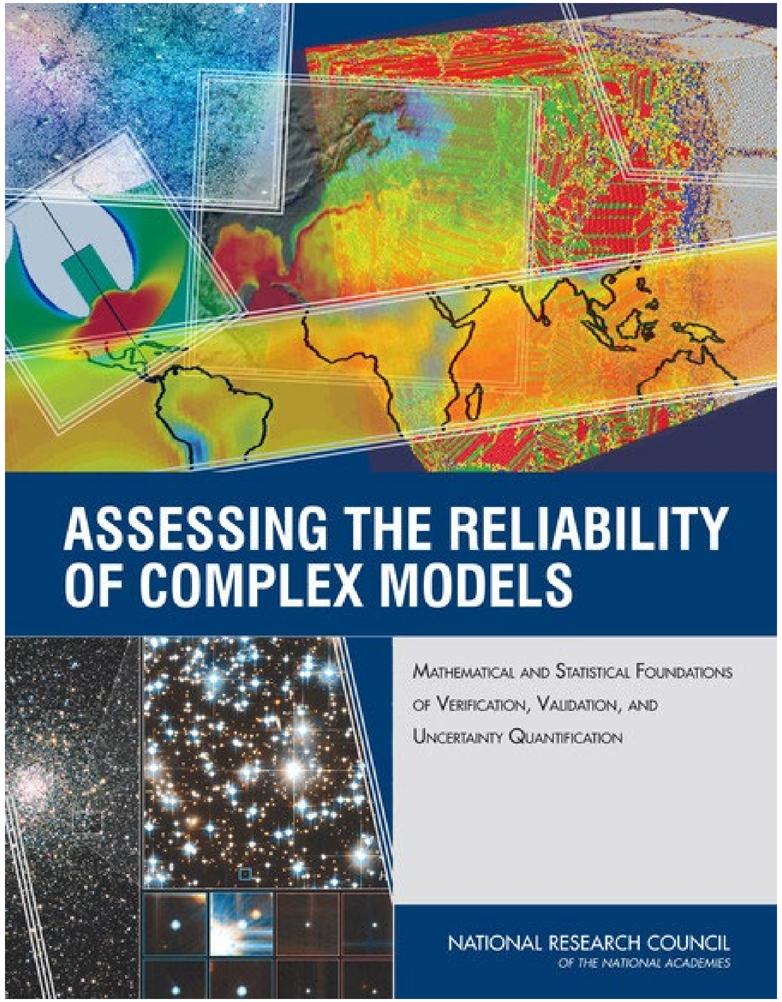
Learn more:

- **Feature story** on unlocking the promise of digital twins
- **Infographic**: Digital Twin of a Cancer Patient
- **Report and report release recording**
- **Workshop proceedings**
  - Atmospheric sciences
  - Engineering
  - Biomedical research
- **May webinar recordings**
  - Ethical implications
  - Regulatory approaches
  - Human interactions
  - In Social and behavioral contexts

https://www.nationalacademies.org/digital-twins

Upcoming Event: Exploring Verification, Validation, and Uncertainty Quantification

- Free, hybrid event on **June 17**:
  Assessing the Reliability of Complex, Dynamic Modeling and Simulation
- Speakers include:
  - Natalia Alexandrov (NASA),
  - David Higdon (Virginia Tech),
  - Peter Jan van Leeuwen (Colorado State University),
  - and Ralph Smith (North Carolina State University)
  - with keynote speaker Thomas Braun (NGA).



ASSESSING THE RELIABILITY OF COMPLEX MODELS

Mathematical and Statistical Foundations of Verification, Validation, and Uncertainty Quantification

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

Federal Government Perspectives on Digital Twins

Stacey Levine, Program Director, Division of Mathematical Sciences, NSF

Daniel Linzell, Division Director, Civil, Mechanical and Manufacturing Innovation, NSF

Chris Saldaña, Director, Advanced Materials and Manufacturing Office, DOE-EERE

Brian Bothwell, Director, Director, Science, Technology Assessment, and Analytics, GAO

Lance Marrano, Science and Technology Advisor for Tyndall AFB Reconstruction Program Office, ERDC, US Army Corps of Engineers

Michael Pease, Mechanical Engineer, NIST

National Science Foundation and Digital Twins

- Foundational Math, Stats, Computation, Science, and Engineering that enables digital twins in practice, both cross-cutting and fit-for-purpose.

- Identify critical ethics, equity, accessibility, security and future workforce development needs.

- Interagency Collaboration, Workshops, Solicitations
  - Research Workshops and Interagency Program Day
  - Two new cross-agency Digital Twin solicitations
    - NSF 24-559: MATH-DT (NSF-AFOSR)
    - NSF 24-561: FDT-BioTech (NSF-NIH-FDA)
  - NITRD - Fast Track Action Committee
    - Digital Twins Research and Development (R&D) Strategic Plan

Earth Systems

Biotechnology

Smart Cities

Manufacturing

Power Grid

Built Environment

Mathematical, Statistical, Computational Foundations

NSF

Stacey Levine, Program Director

Division of Mathematical Sciences

Directorate for Mathematical and Physical Sciences

Opportunities for Digital Twins in the Built Environment

CMMI Perspective and Examples

NASEM virtual symposium on digital twins for the built environment
6/12/24

Daniel Linzell, Director, Division of Civil, Mechanical and Manufacturing Innovation

dlinzell@nsf.gov

What is a digital twin – CMMI context

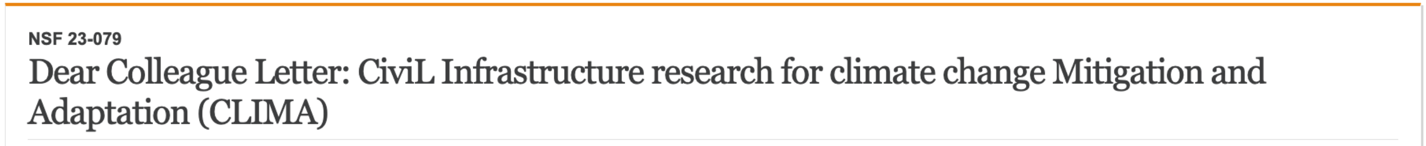
CMMI funds potentially transformative research to enable advances in:

- Manufacturing and building technologies across size scales from nanometers to kilometers, with emphases on efficiency, economy, and minimal environmental footprint.
- Efficient, economical and sustainable transformation and use of engineering materials.
- **Resilient and sustainable civil infrastructure and distributed infrastructure networks.**
- **Advances in the creation of models, analyses, and algorithms that link data with decisions** related to manufacturing and service enterprises.
- Design, control, and optimization methods applied at levels ranging from component to enterprise systems.

Civil, Mechanical and Manufacturing Innovation (CMMI)

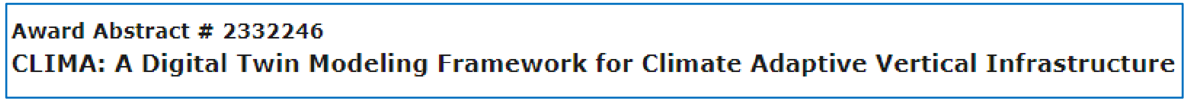
Advances the future of manufacturing, the design of innovative materials and building technologies, infrastructure resilience and sustainability, and tools and systems for decision-making, robotics and controls.

What is a digital twin in CMMI context?? BUILT ENVIRONMENT



NSF 23-079

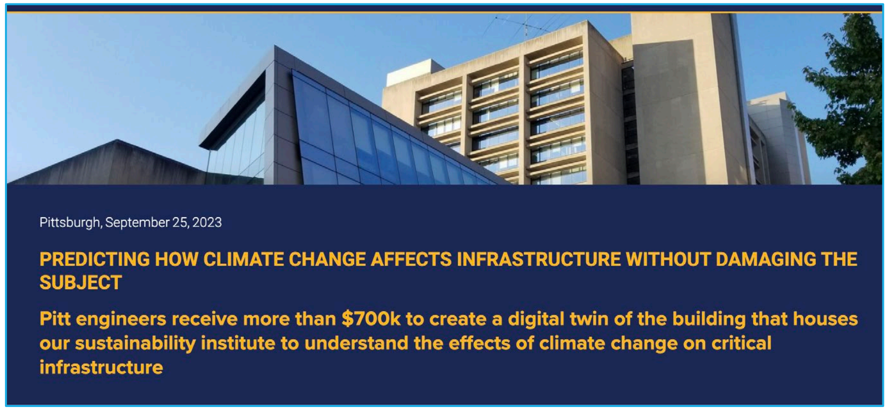
Dear Colleague Letter: CiviL Infrastructure research for climate change Mitigation and Adaptation (CLIMA)



Award Abstract # 2332246

CLIMA: A Digital Twin Modeling Framework for Climate Adaptive Vertical Infrastructure

*This award supports research focusing on developing a **novel Digital Twin framework for the quantification of Greenhouse Gas (GHG) emissions associated with the operation of vertical infrastructure and minimizing such environmental footprint** by designing and deploying environmentally responsive building envelopes.*

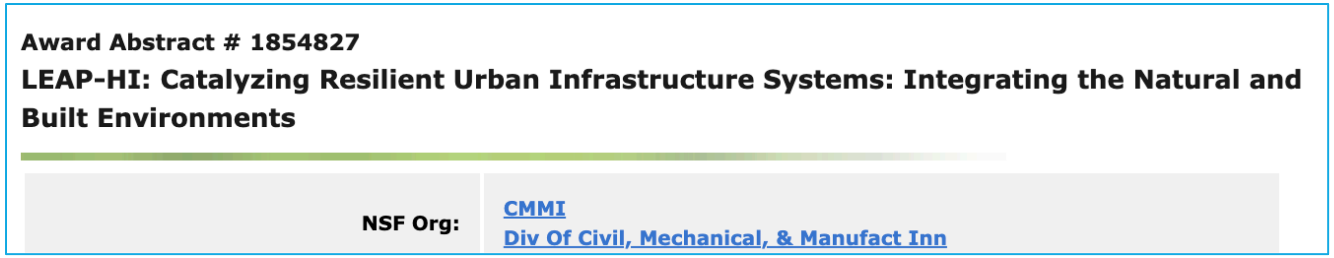


Pittsburgh, September 25, 2023

PREDICTING HOW CLIMATE CHANGE AFFECTS INFRASTRUCTURE WITHOUT DAMAGING THE SUBJECT

Pitt engineers receive more than $700k to create a digital twin of the building that houses our sustainability institute to understand the effects of climate change on critical infrastructure

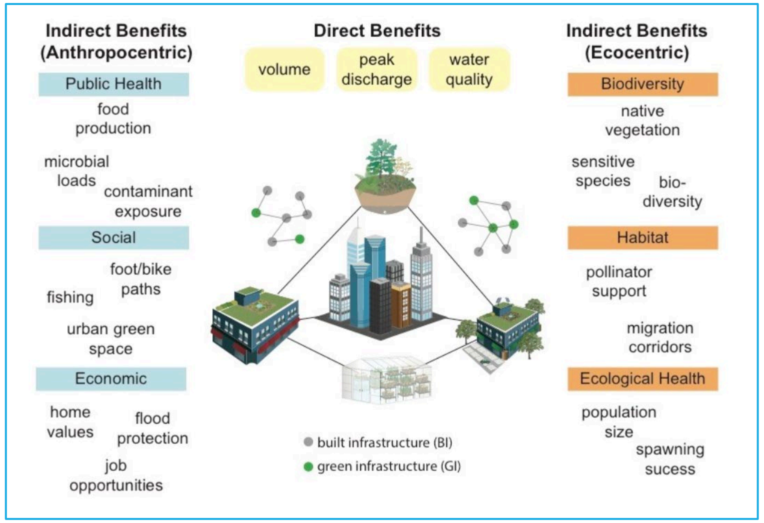
What is a digital twin in CMMI context?? BUILT ENVIRONMENT

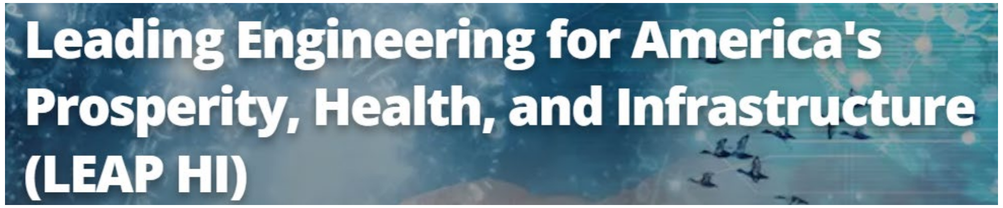


Award Abstract # 1854827

LEAP-HI: Catalyzing Resilient Urban Infrastructure Systems: Integrating the Natural and Built Environments

NSF Org:	CMMI Div Of Civil, Mechanical, & Manufact Inn





Leading Engineering for America's Prosperity, Health, and Infrastructure (LEAP HI)

*The overarching goal of this LEAP-HI project is **to research the engineering tools (sensor network, data acquisition, model development, and network design) that will allow the integration of Green Infrastructure (GI) networks with existing Built Infrastructure (BI) for the management of stormwater** with systems-level, predictive performance and quantitative assessment of costs and expanded benefits, including water quality, biodiversity and community well-being.*


NSF

Digital Twins at the US Department of Energy

Supporting Clean Energy RD&D

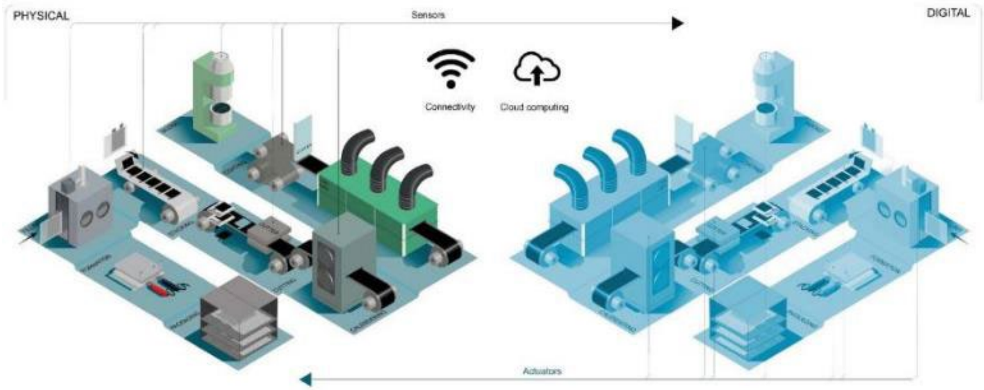
Platform Technologies

- <u>Manufacturing Technologies</u>: smart mfg, digital twin, AI/ML, cybersecurity, high performance computing, roll-to-roll, additive, circularity
- <u>Advanced Materials</u>: composites, critical materials, high conductivity and harsh condition materials
- <u>Workforce</u>: training, curricula, entrepreneurship

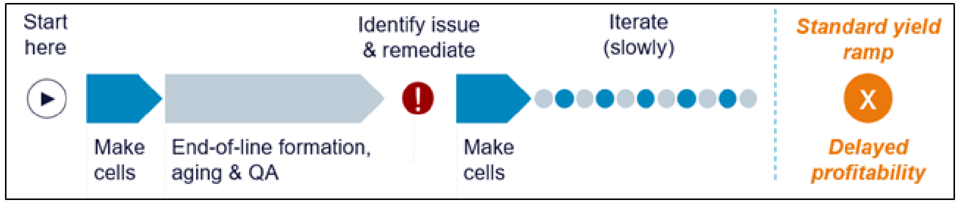
AMMTO Consortia

CMI
Oak Ridge National Laboratory Manufacturing Demonstration Facility
Oak Ridge National Laboratory Carbon Fiber Technology Facility
U.S. Department of Energy LEEP Lab-Embedded Entrepreneurship Program
HPC4 Manufacturing
PowerAmerica
iacmi
REMADE Institute
CYMANII
CESMII The Smart Manufacturing Institute

Vision: Facility-level digital twins

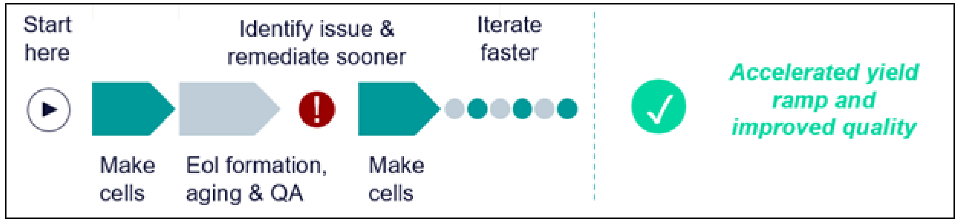


Conventional Battery Production



Start here
Make cells
End-of-line formation, aging & QA
Identify issue & remediate
Make cells
Iterate (slowly)
Standard yield ramp
X
Delayed profitability

Smart Manufacturing for Battery Production



Start here
Make cells
Eol formation, aging & QA
Identify issue & remediate sooner
Make cells
Iterate faster
✓
Accelerated yield ramp and improved quality

Voltaiq, 2023.

Opportunities

- Manufacturing and engineering efficiency
- Improved health care

Challenges

- Privacy and ethical issues
- Technical and infrastructure barriers
- Economic costs
- Standards and regulations

Brian Bothwell
Director
U.S. Government Accountability Office

GAO-23-106453
Science & Tech Spotlight:
Digital Twins

Tyndall Digital Twin

Near life-like virtual representation of the physical world

- Accelerate **data-driven** decision-making with **intuitive visualization**
- Empower organizations through **modeling and simulation** capabilities

Hangar 1, Hangar 2, Hangar 3, Tyndall HQ, LRS Vehicle Maintenance, Building 585 Classrooms; Building 588, F-22 SIM/AC Facility. Projection for September 2026.

DIGITIZE

- Reality capture of assets through multiple sensor and scanning platforms.

CENTRALIZE

- Connect and explore diverse, interrelated datasets, from SMS to BIM to geospatial.

DEMOCRATIZE

- Intuitive platform makes data available to both technical and non-technical users across the Air Force enterprise.

UTILIZE

- Flexible, scalable model enables countless use cases across many installation and mission stakeholders.

STATUS

- 77 existing facilities; 105 new facilities
- FY24 priorities: Authority to Operate (ATO); Expand CE support use cases

Same Tools as other USAF Communities - supports **Future Collaboration** and **Integration**

Digital Twins for Facility Operations

2

Burcu Akinci, Carnegie Mellon University

Specialized and Highly-Regulated Applications – Nuclear Facilities

Vaibhav Yadav, Idaho National Laboratory

3

Vaibhav Yadav, PhD.
Senior Scientist
Nuclear Safety and Regulatory Research Division

INL/MIS-24-77107

Developing Digital Twins for Nuclear Energy Applications

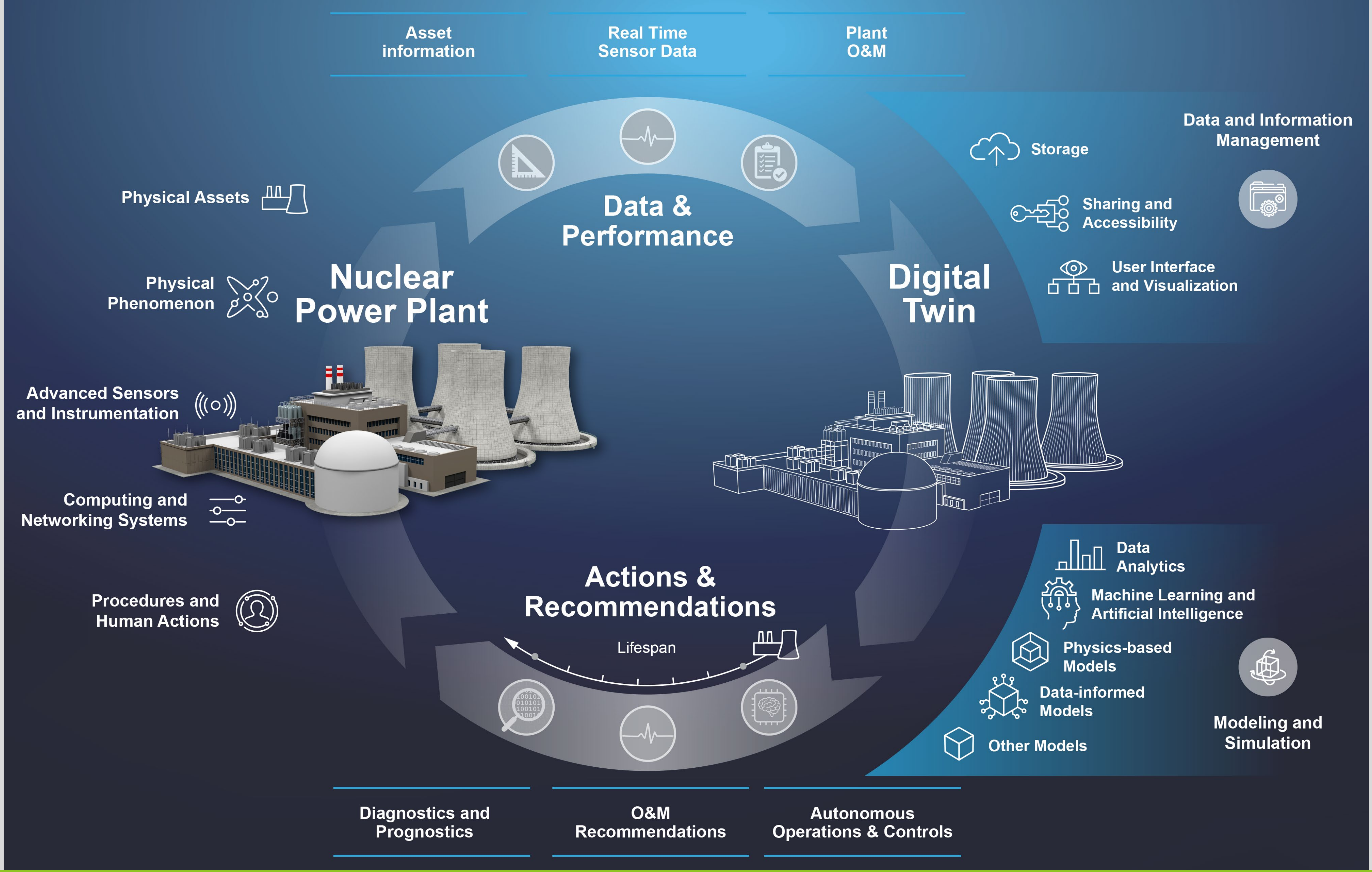
Opportunities for Digital Twins in the Built Environment

Webinar

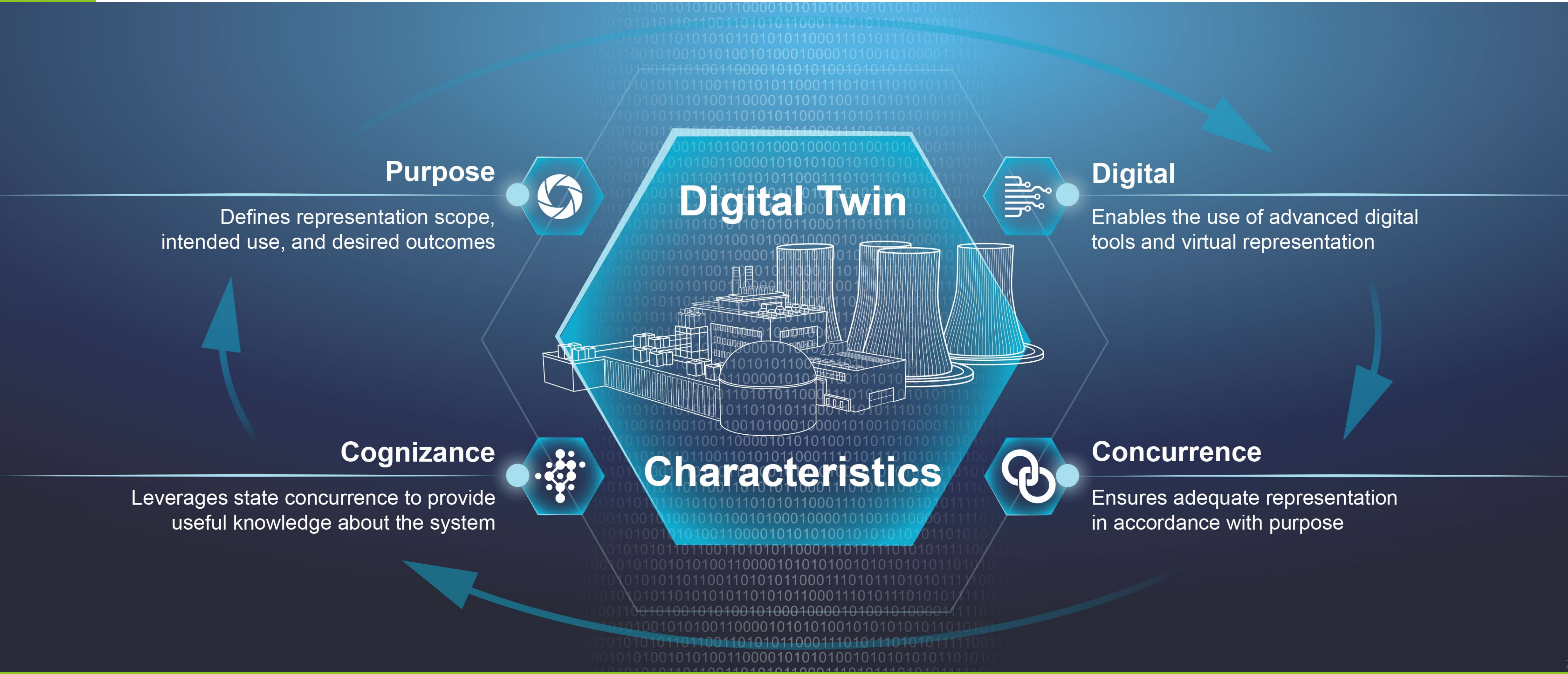
June 13, 2024

INL is managed by Battelle Energy Alliance
for the US Department of Energy

Idaho National Laboratory


Asset information
Real Time Sensor Data
Plant O&M
Data & Performance
Physical Assets
Physical Phenomenon
Nuclear Power Plant
Advanced Sensors and Instrumentation
Computing and Networking Systems
Procedures and Human Actions
Digital Twin
Data and Information Management
Storage
Sharing and Accessibility
User Interface and Visualization
Data Analytics
Machine Learning and Artificial Intelligence
Physics-based Models
Data-informed Models
Other Models
Modeling and Simulation
Actions & Recommendations
Lifespan
Diagnostics and Prognostics
O&M Recommendations
Autonomous Operations & Controls

Characteristics of Digital Twin



Purpose

Defines representation scope, intended use, and desired outcomes

Digital

Enables the use of advanced digital tools and virtual representation

Cognizance

Leverages state concurrence to provide useful knowledge about the system

Concurrence

Ensures adequate representation in accordance with purpose

Key Applications of DT in Nuclear

- Reactor system design and analysis
  - DT to support design iterations, optimization, prototyping, and construction
  - Plant-referenced simulators and operator training
- Operations
  - DT to inform and recommend actions
  - DT informed or autonomous controls
- Maintenance
  - Inservice Inspection and Testing (ISI & IST)
- Regulations
  - Licensing, Oversight, Operational experience, Support for Decision
- Safety, Security, and Safeguards

Letter Report
TLR-RES/DE/REB-2022-06

REGULATORY CONSIDERATIONS FOR NUCLEAR ENERGY APPLICATIONS OF DIGITAL TWIN TECHNOLOGIES

August 2022

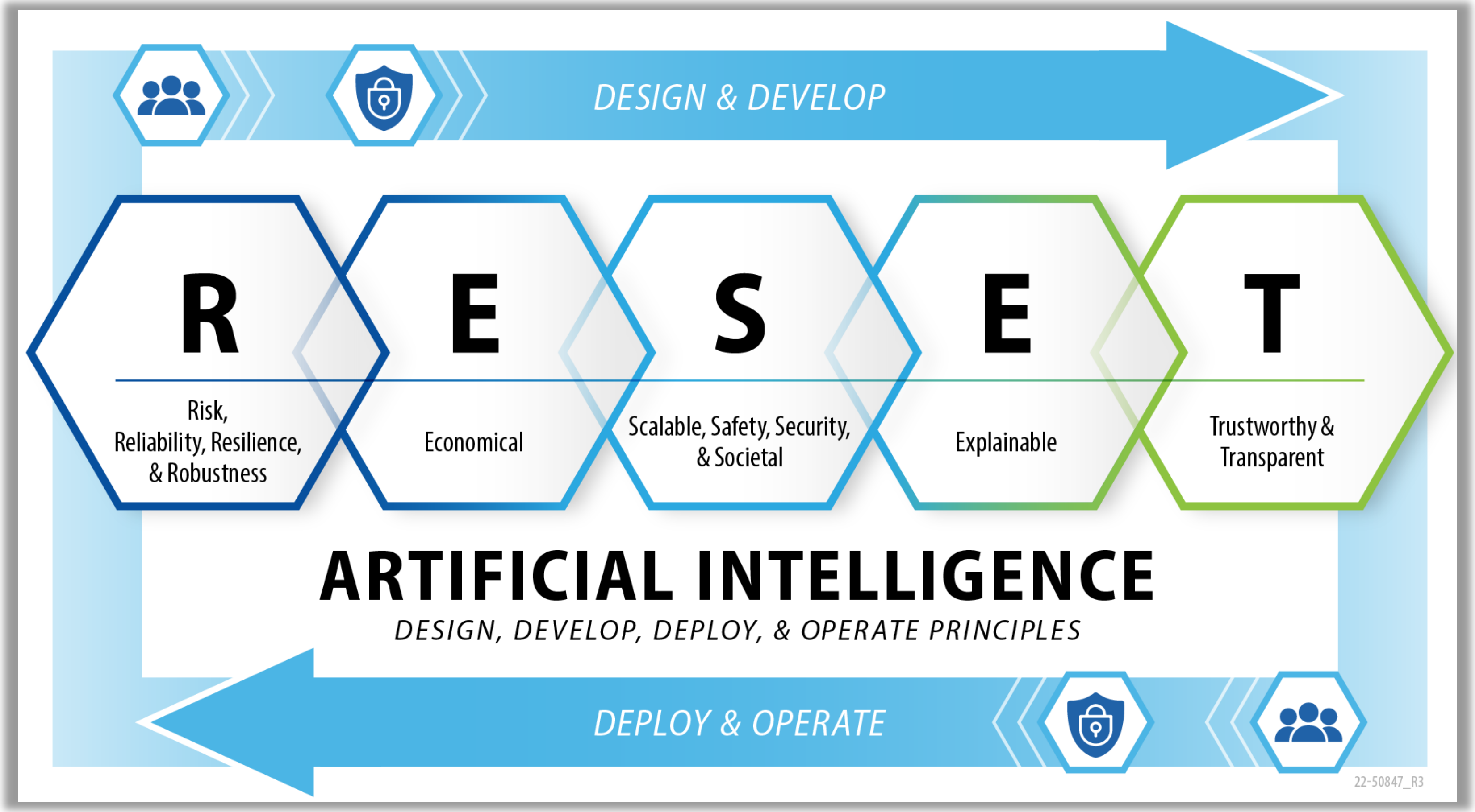
V. Yadav, A. Wells, C. Pope, J. Andrus,
C. Chwasz, T. Trask
Idaho National Laboratory

D. Eskins, J. Carlson, C. Ulmer,
N. Chandran, R. Iyengar
U.S. Nuclear Regulatory Commission

Division of Engineering
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555–0001

Prepared as part of the Task Order 31310020F0063, "Technical Support for Assessment of Regulatory Viability of Digital Twins"

US DOE Light Water Reactor Sustainability Program



DESIGN & DEVELOP

R
Risk, Reliability, Resilience, & Robustness

E
Economical

S
Scalable, Safety, Security, & Societal

E
Explainable

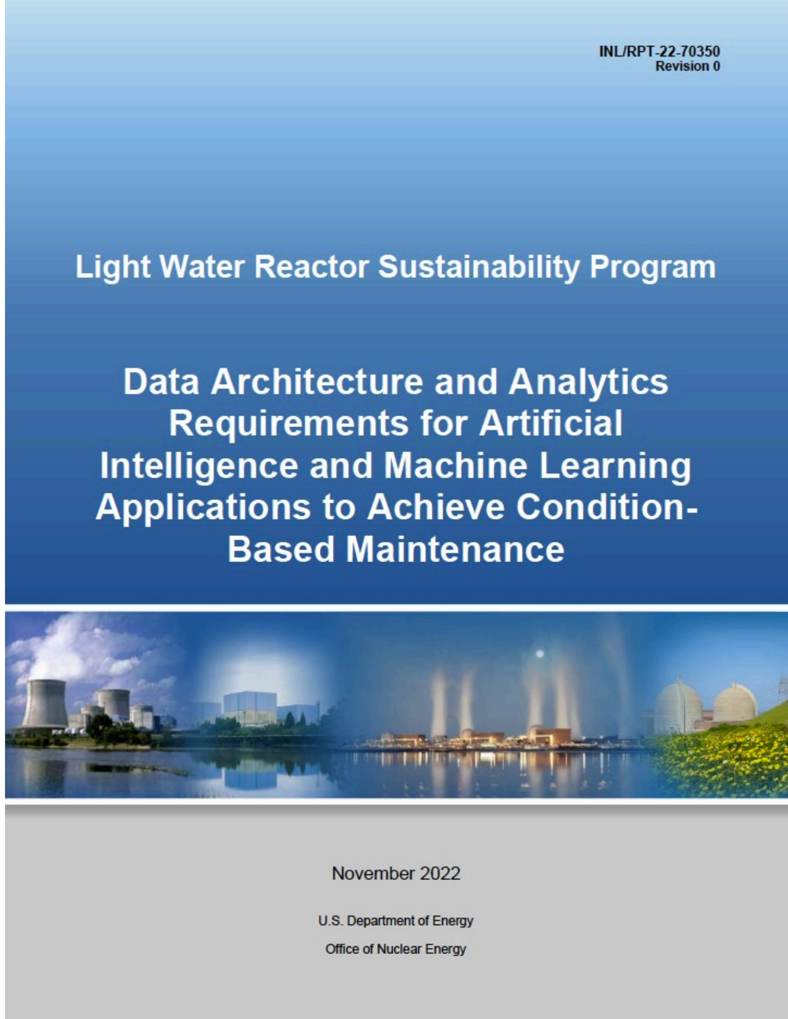
T
Trustworthy & Transparent

ARTIFICIAL INTELLIGENCE

DESIGN, DEVELOP, DEPLOY, & OPERATE PRINCIPLES

DEPLOY & OPERATE

22-50847_R3



INL/RPT-22-70350
Revision 0

Light Water Reactor Sustainability Program

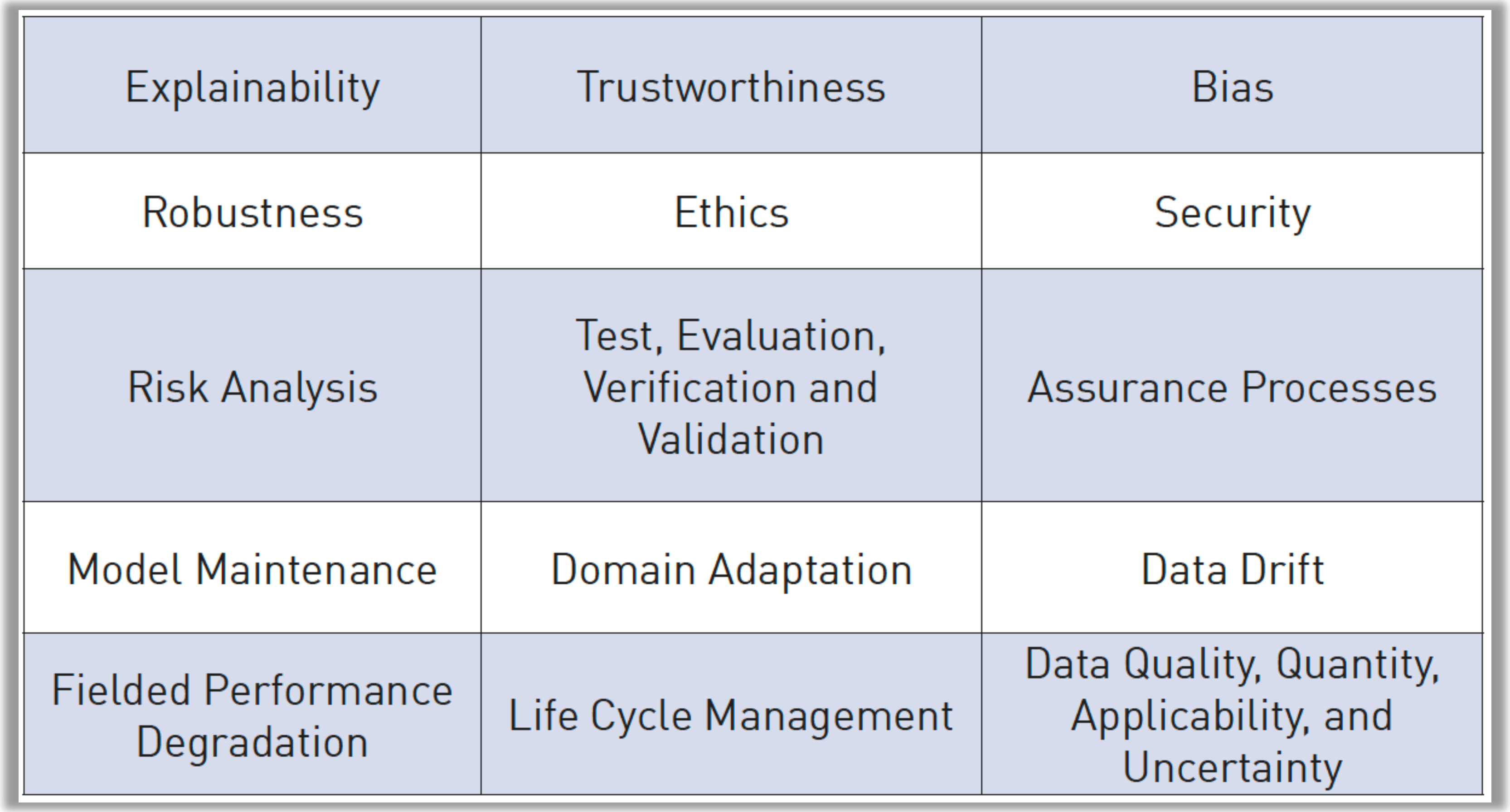
Data Architecture and Analytics Requirements for Artificial Intelligence and Machine Learning Applications to Achieve Condition-Based Maintenance

November 2022

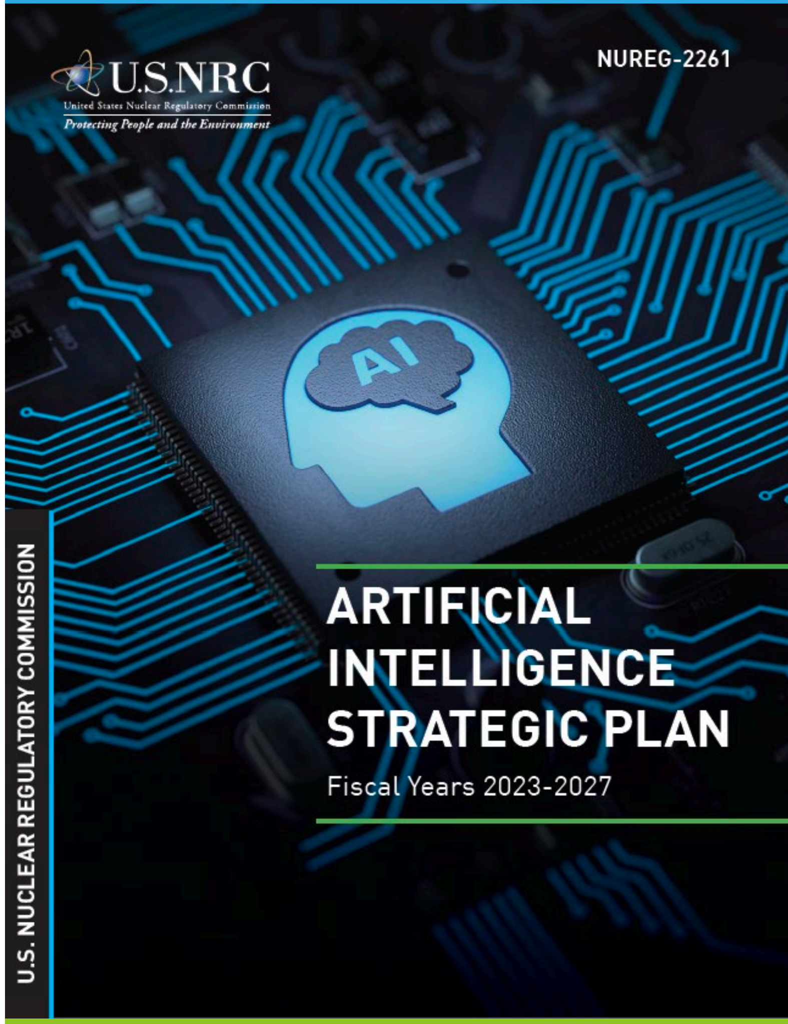
U.S. Department of Energy
Office of Nuclear Energy

NRC AI Strategic Plan

Technical Considerations for Regulatory Decision Making



Explainability	Trustworthiness	Bias
Robustness	Ethics	Security
Risk Analysis	Test, Evaluation, Verification and Validation	Assurance Processes
Model Maintenance	Domain Adaptation	Data Drift
Fielded Performance Degradation	Life Cycle Management	Data Quality, Quantity, Applicability, and Uncertainty



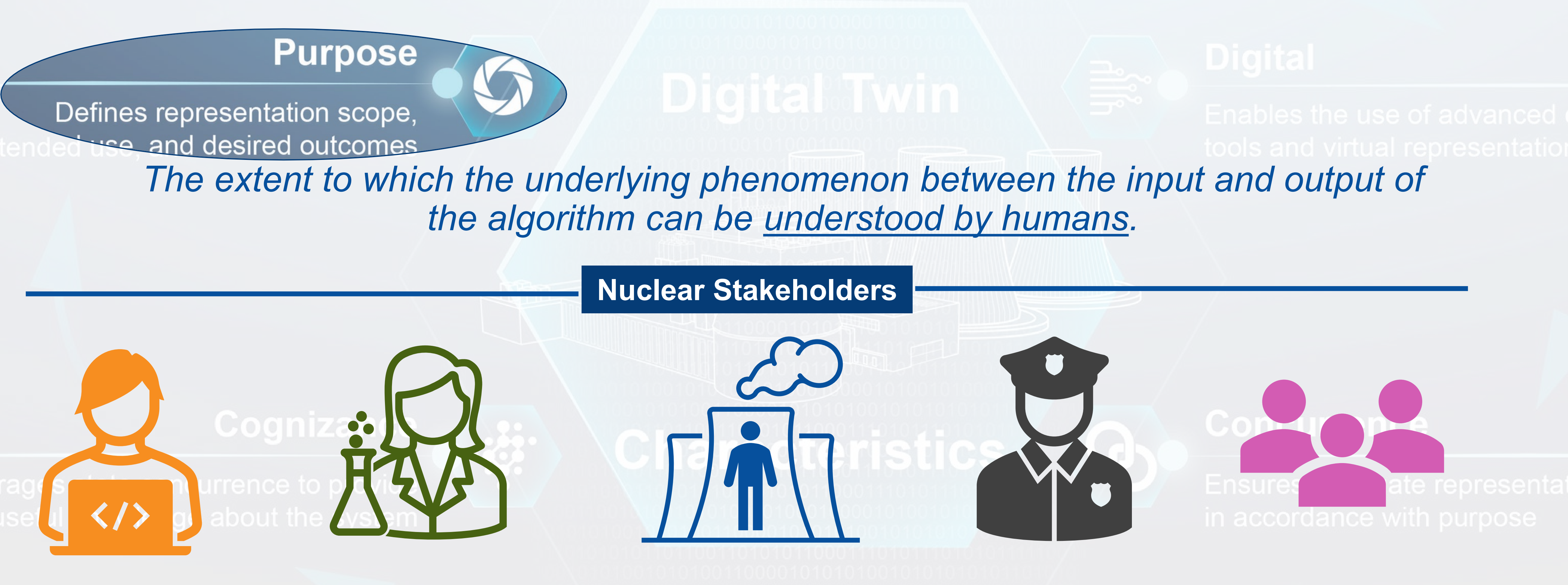
U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

NUREG-2261

U.S. NUCLEAR REGULATORY COMMISSION

ARTIFICIAL INTELLIGENCE STRATEGIC PLAN
Fiscal Years 2023-2027

Explainability



Purpose

Defines representation scope, tended use, and desired outcomes

The extent to which the underlying phenomenon between the input and output of the algorithm can be understood by humans.

Nuclear Stakeholders

Developers

Researchers

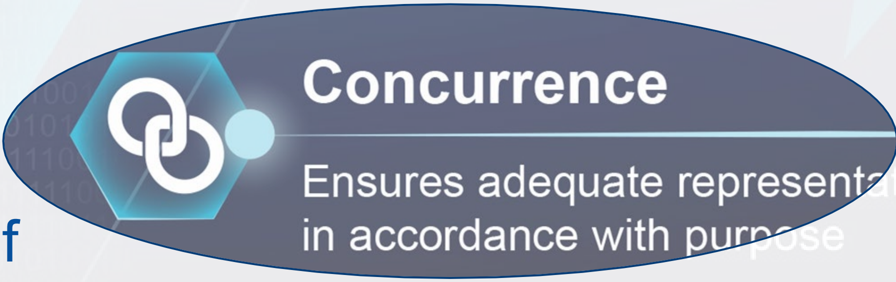
Plant Staff

Regulators

Others

Considerations for Maintaining Real Time Concurrence

- Verification, Validation and Uncertainty Quantification
  - Real time verifiability and interface
  - Robustness
- Data Quality and Data Reliability
  - Legacy data & real time data
- Big data consideration in real time
  - 3V: Velocity – Volume – Veracity
  - Complexity: dependencies, non-linearity etc.
- Model selection
  - Computational requirements for real time running of the models
- Real time communication
  - AI ⇔ Other models

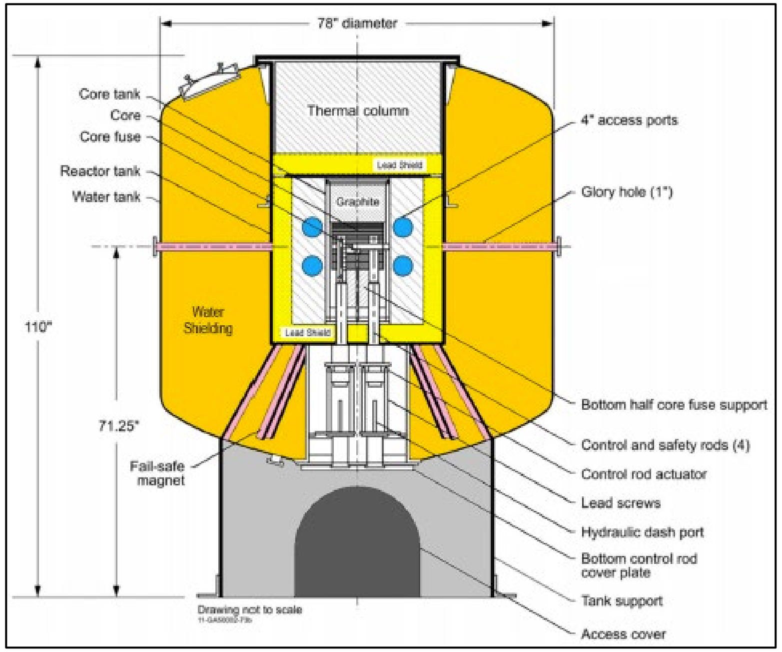


All About Nuclear Digital Twin

1	The **State of Technology** of Application of Digital Twins
2	Technical **Challenges and Gaps in Digital-Twin-Enabling Technologies** for Nuclear Reactor Application
3	**Regulatory Considerations** for Nuclear Energy Applications of Digital Twin Technologies
4	State of Technology and Technical Challenges in **Advanced Sensors, Instrumentation, and Communication** to Support Digital Twin for Nuclear Energy Application
5	Digital Twins for **Nuclear Safeguards and Security**: Assessment of Challenges, Opportunities, and Current State-of-Practice
6	**Project Summary** of Digital Twin Regulatory Viability in Nuclear Energy Applications
7	Proceedings of the **Workshop** on Digital Twin Applications for Advanced Nuclear Technologies
8	Proceedings of the **Workshop** on Enabling Technologies for Digital Twin Applications for Advanced Reactors and Plant Modernization

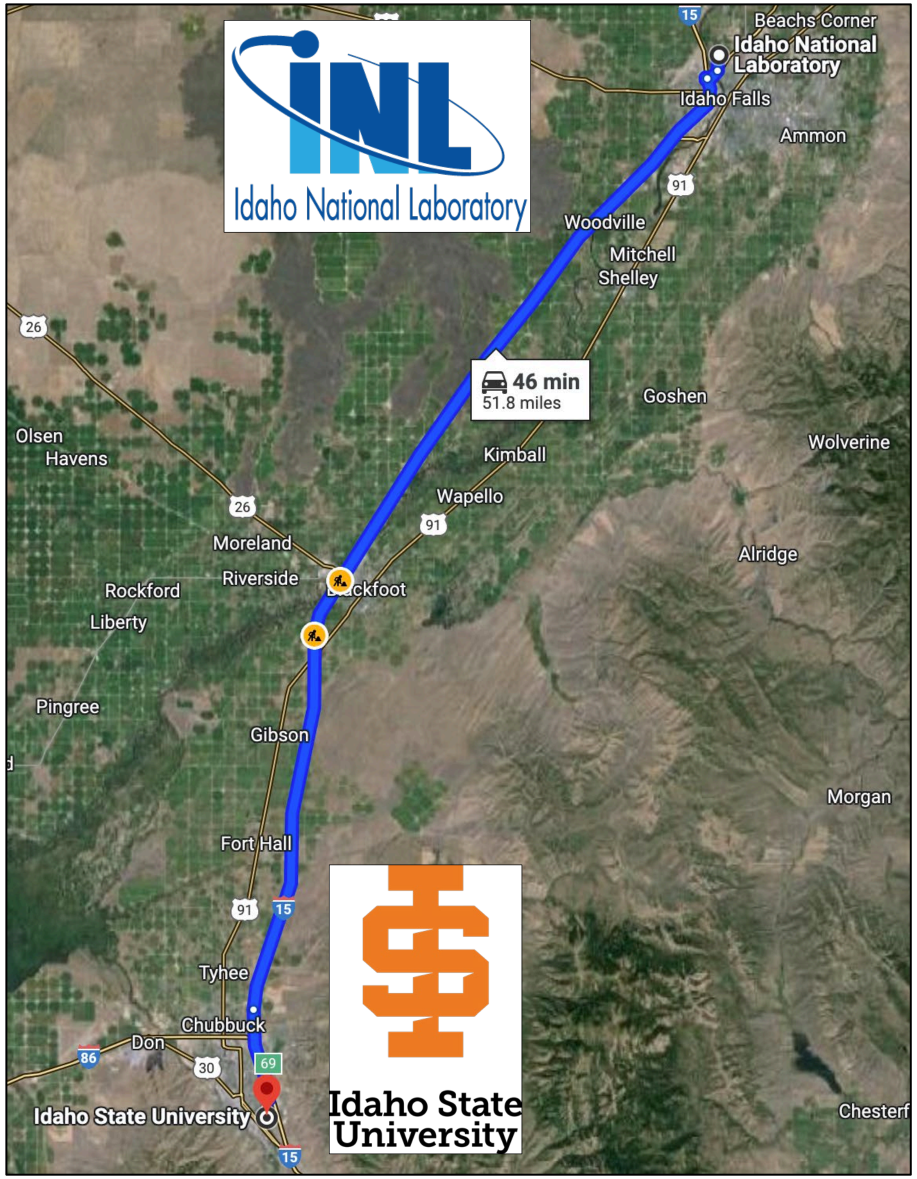
https://www.nrc.gov/reactors/power/digital-twins.html

Research Reactor DT at INL



ISU Aerojet General Nucleonics (AGN)-201 Reactor

Yockey W, Ali A, Pope C. Development of a new control rod drive mechanism design for the ISU AGN-201M reactor. Annals of Nuclear Energy. 2022 Mar 1;167:108817.



Idaho researchers develop reactor digital twin

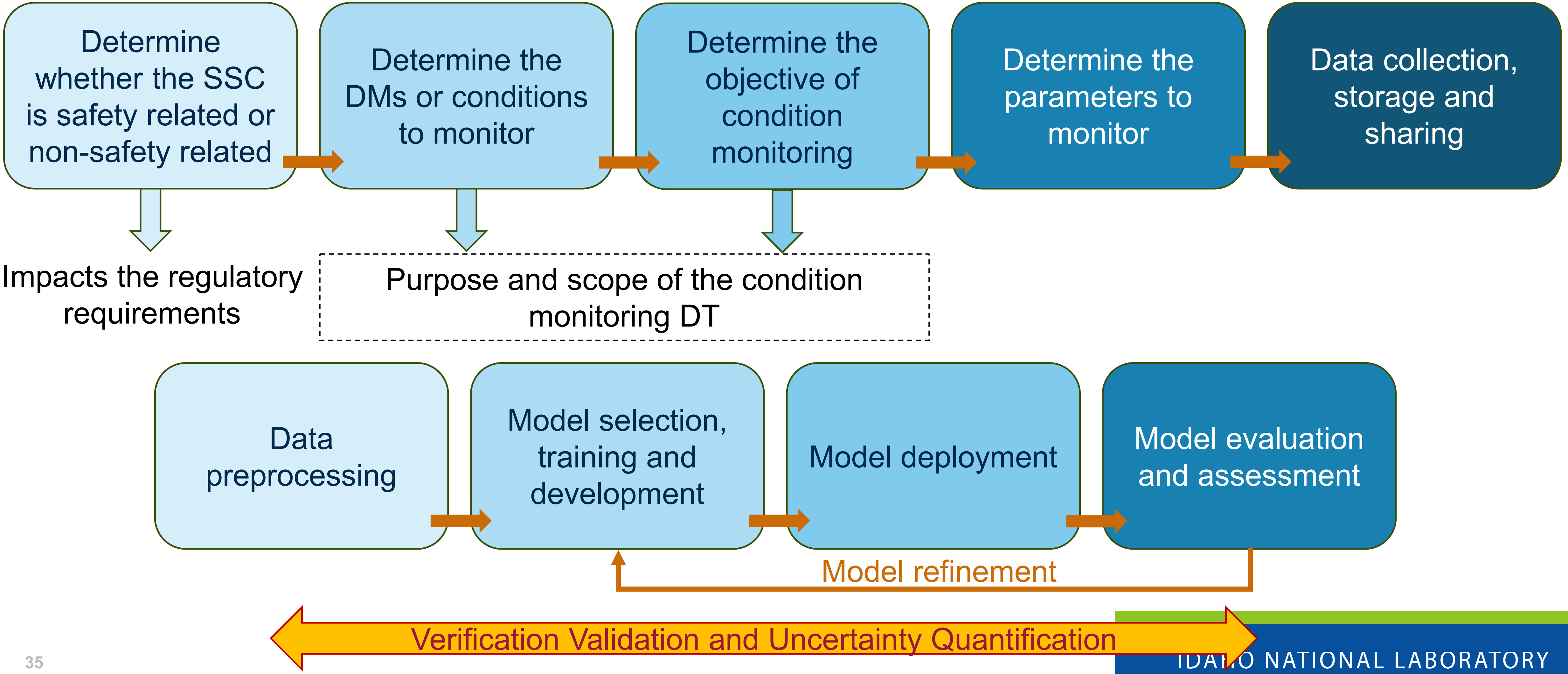
04 January 2024

Share

A virtual replica of Idaho State University's (ISU's) AGN-201 research reactor, developed in collaboration with Idaho National Laboratory (INL), is claimed to be the world's first nuclear reactor digital twin.

The team checks out a component of the reactor digital twin (Image: INL)

DT for Condition Monitoring of Active Components in Nuclear Power Plants



Determine whether the SSC is safety related or non-safety related

Determine the DMs or conditions to monitor

Determine the objective of condition monitoring

Determine the parameters to monitor

Data collection, storage and sharing

Impacts the regulatory requirements

Purpose and scope of the condition monitoring DT

Data preprocessing

Model selection, training and development

Model deployment

Model evaluation and assessment

Model refinement

Verification Validation and Uncertainty Quantification

Battelle Energy Alliance manages INL for the U.S. Department of Energy's Office of Nuclear Energy. INL is the nation's center for nuclear energy research and development, and also performs research in each of DOE's strategic goal areas: energy, national security, science and the environment.

WWW.INL.GOV

Digital twin for hydropower systems: opportunities on operational optimization and smart maintenance

4

Hong Wang, Oak Ridge National Laboratory
Chitra Sivaraman, Pacific Northwest National Laboratory

U.S. DEPARTMENT OF
ENERGY

Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY

Digital Twin for Hydropower Systems: Opportunities on Operational Optimization and Smart Maintenance

Hong Wang, PI
Fellow of IEEE, IET, InstMC, AAIA and AIIA,
Senior Distinguished0 Scientist
Oak Ridge National Laboratory

OAK RIDGE
National Laboratory

Team Composition and Acknowledgement

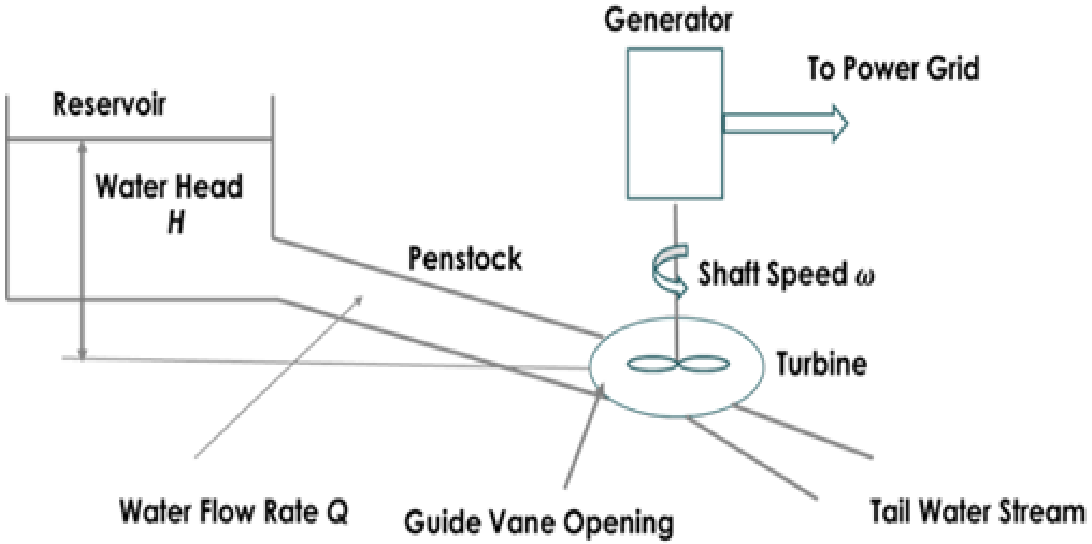
- Pacific Northwest National Laboratory, led by Chitra Sivaraman
- New York University
- Norwegian University of Science and Technology (NTNU)
- Tacoma Public Utilities
- Chelan County Public Utility District

The work is funded by Water Power Technologies Office of the US Department of Energy

Hydropower - Challenges and Needs for Digital Twin

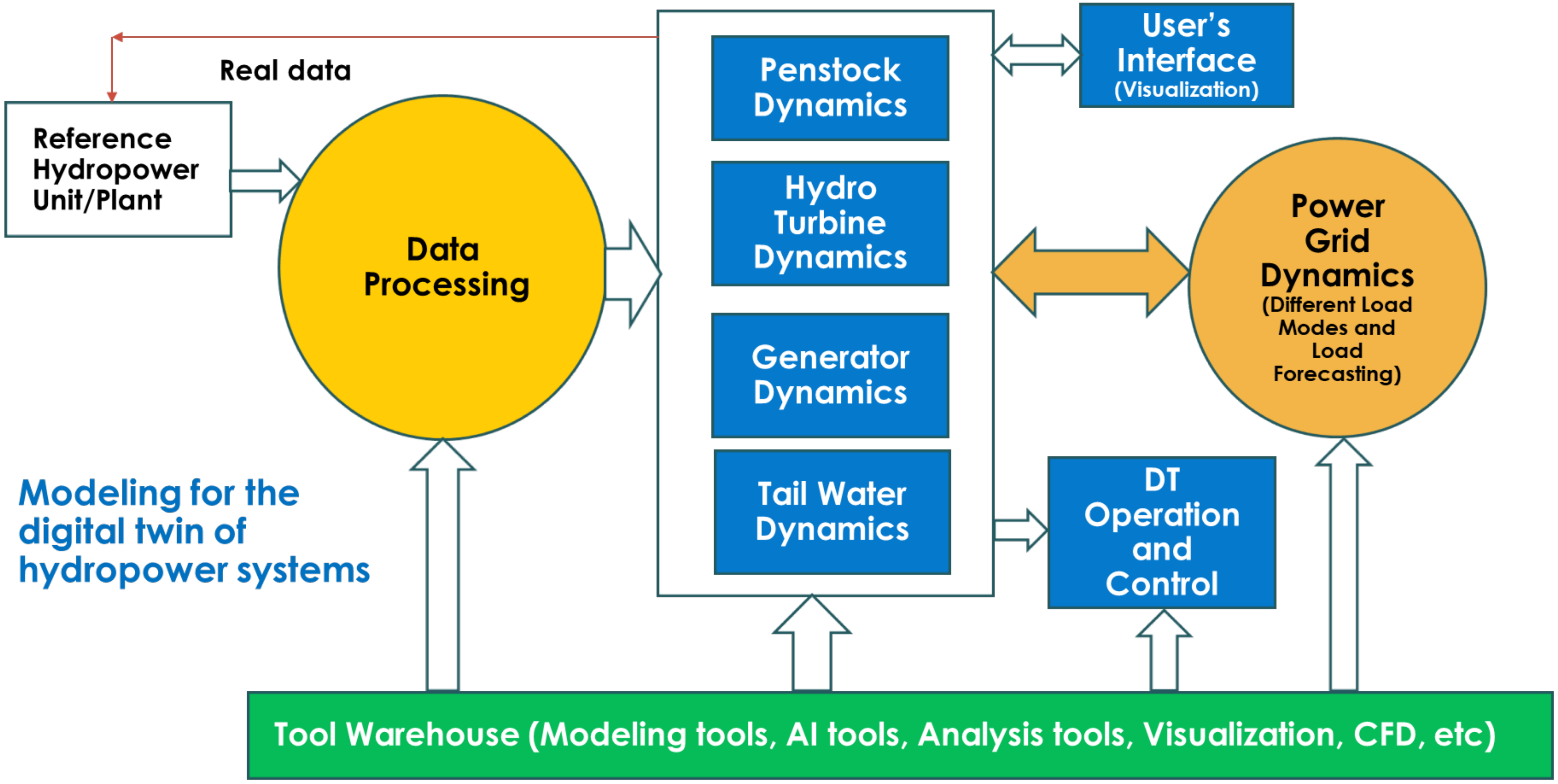
- Background and Challenges
  - Hydro power used to operate around stable operating point, with increased renewable penetration, power grid is operating at large variation range
  - This requires hydro to be responsive and have capability of smart maintenance

Digital Twin (DT) is therefore needed to mimic hydropower systems - allowing large range operational optimization and achieving smart maintenance goal



OAK RIDGE
National Laboratory

DT Scope Design and Modeling Landscape



Modeling for the digital twin of hydropower systems

Water System and Turbine Torque Models

Water System Dynamics: Water system includes reservoir, penstock, turbine chamber and discharge (tail water stream)

$$Q = f(H, \omega, u)$$

where H is the operating water height, u is the inlet valve opening to the turbine, ω is the turbine shaft speed, f is a complicated nonlinear equation obtained from fluid dynamic and is generally learned via first principle and AI-based data driven modeling (neural networks, etc.)

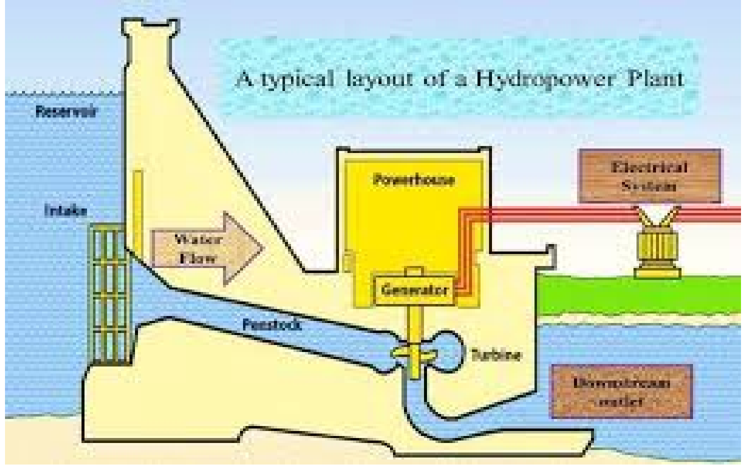
Water System Dynamics

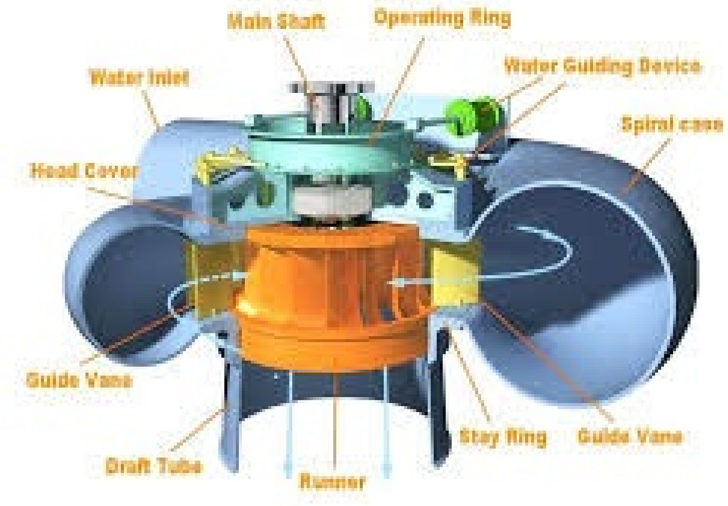
$$\frac{dQ}{dt} = \pi(H)$$ – partial differential equations required

Mechanical Torque to Turbine Shaft

$$M = g(H, \omega, u)$$

where g(…) is a nonlinear function that requires artificial intelligence-based data driven modelling, together with initial data base from turbine manufacturers, which requires neural networks.





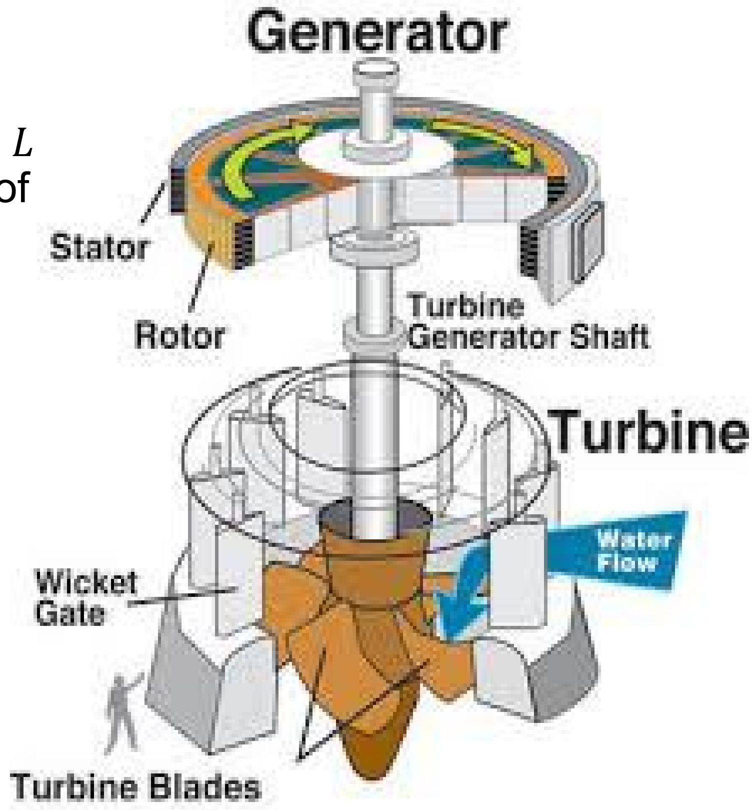
Francis Turbine

Power Generation Systems - Voltage Control Models

Turbine System Dynamics

- $J\frac{d\omega}{dt} = M - L; \quad f = \frac{p}{120}\omega\ (Hz) = 60Hz$

where ω is the shaft speed in rpm, J is the inertia, M is the mechanical torque and L is the load torque related to the power supplied to the grid, p is the pole numbers of the stator of synchronous generator.

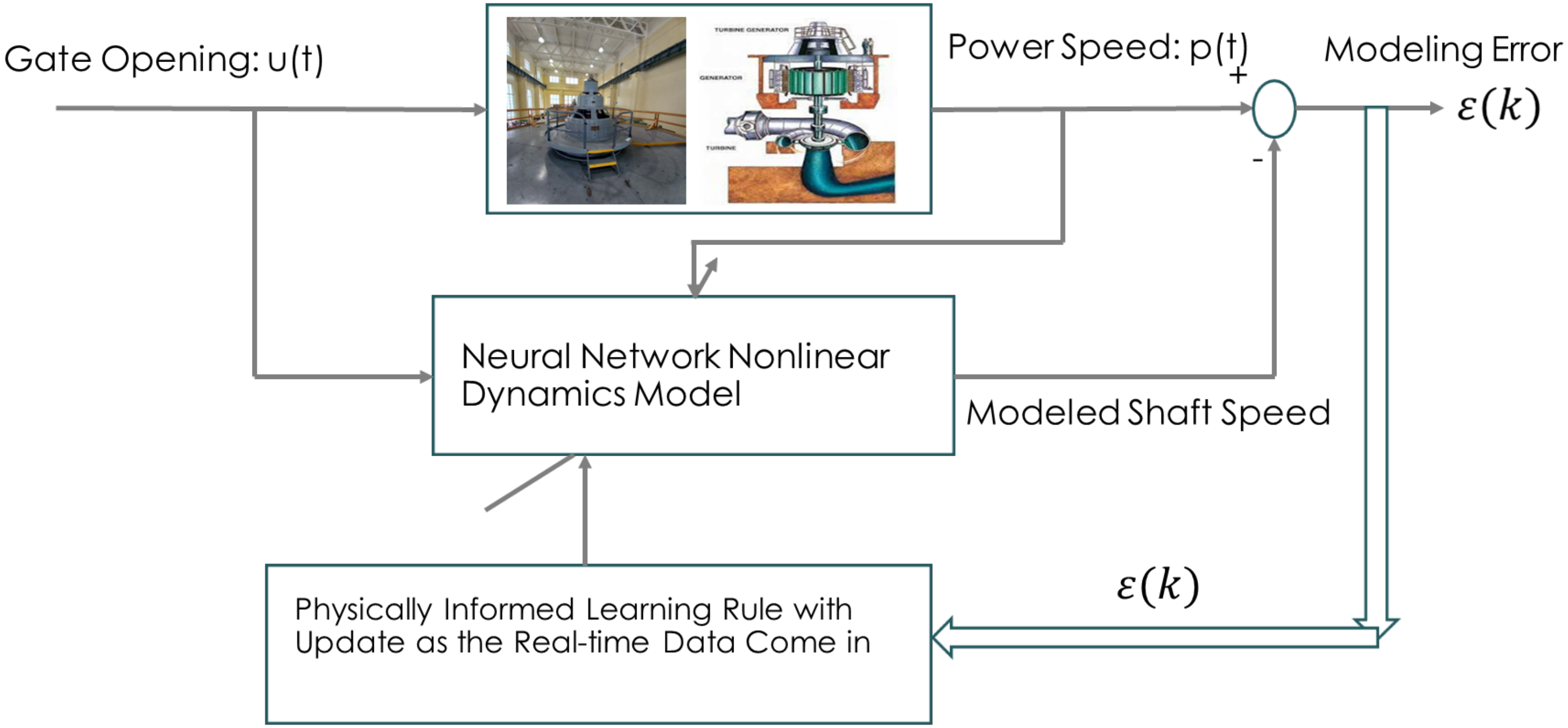


Interaction with Grid via Load Torque

- $L \sim P_e$
  - Where P_e is the active power represented by
- $\begin{bmatrix} P_e \\ Q_e \end{bmatrix} = \begin{bmatrix} V_{gd} & V_{gq} \\ V_{gq} & -V_{gd} \end{bmatrix} \begin{bmatrix} I_d \\ I_q \end{bmatrix}$
- $\begin{bmatrix} V_{gd} \\ V_{gq} \end{bmatrix} = \begin{bmatrix} E_d^{"} \\ E_q^{"} \end{bmatrix} - \begin{bmatrix} 0 & -X_q^{"} \\ X_d^{"} & 0 \end{bmatrix} \begin{bmatrix} I_d \\ I_q \end{bmatrix}, E = \begin{bmatrix} E_d^{"} \\ E_q^{"} \end{bmatrix}, I = \begin{bmatrix} I_d \\ I_q \end{bmatrix}$
- $\frac{dE}{dt} = \aleph(E, I, X_q^{"}, X_d^{"}, v)$
  - Where v is the excitation control input of the generator, others are generators variables, two control inputs, for generation unit (turbine + synchronous generator system), are
  - $\{u = valve\ openning, v = excitation\ control\ input\}$

Leaning Algorithm - Power Control

Key Idea: Use measured system variables to learn system dynamics or nonlinearities



Gate Opening: u(t)

Power Speed: p(t)

Modeling Error

$\varepsilon(k)$

Neural Network Nonlinear Dynamics Model

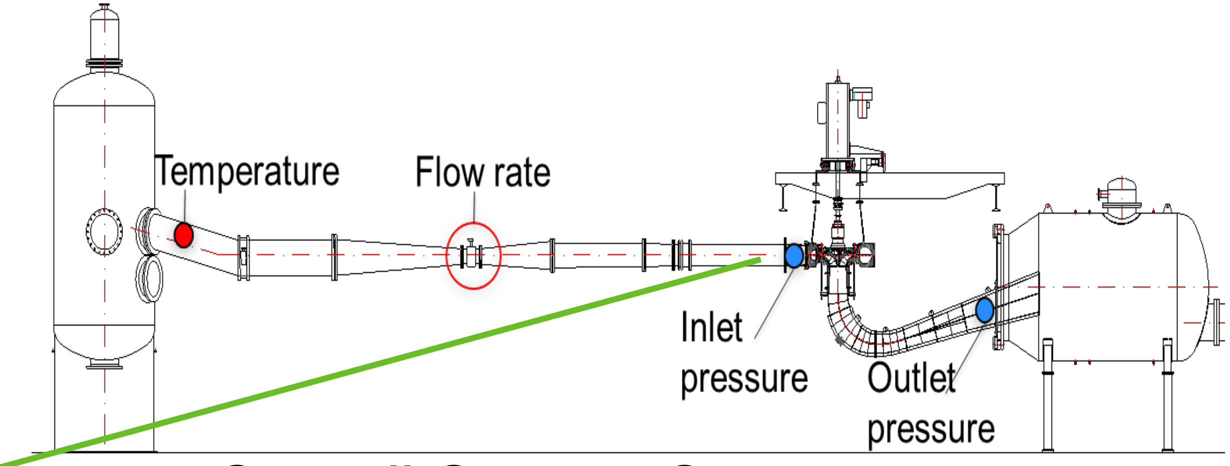
Modeled Shaft Speed

$\varepsilon(k)$

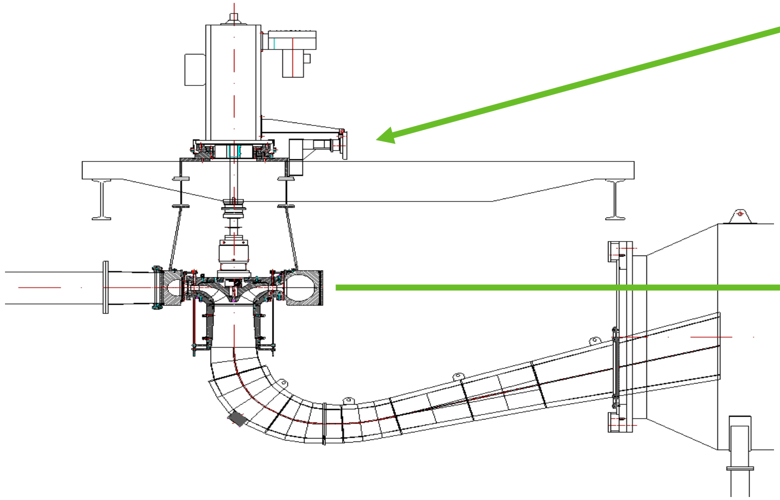
Physically Informed Learning Rule with Update as the Real-time Data Come in

Testing System in Norway (NTNU)

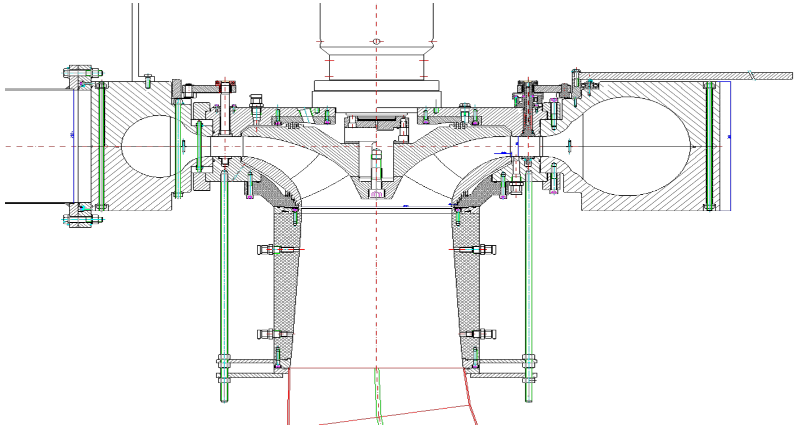
- Model data
  - Head: 12-30 meter
  - Flow rate; 0,1 – 0,4 m^3/s
  - Geometrical scale: 1: 5,1
  - Available data:
    - Complete 3D-geometry
    - Complete hill diagram
    - Pressure pulsations
    - CFD-mesh



Overall System Structure

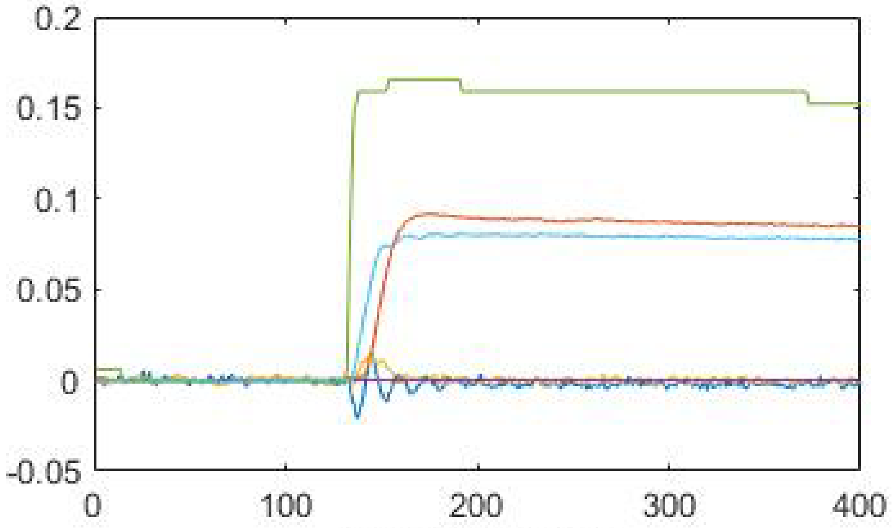


Turbine Complex

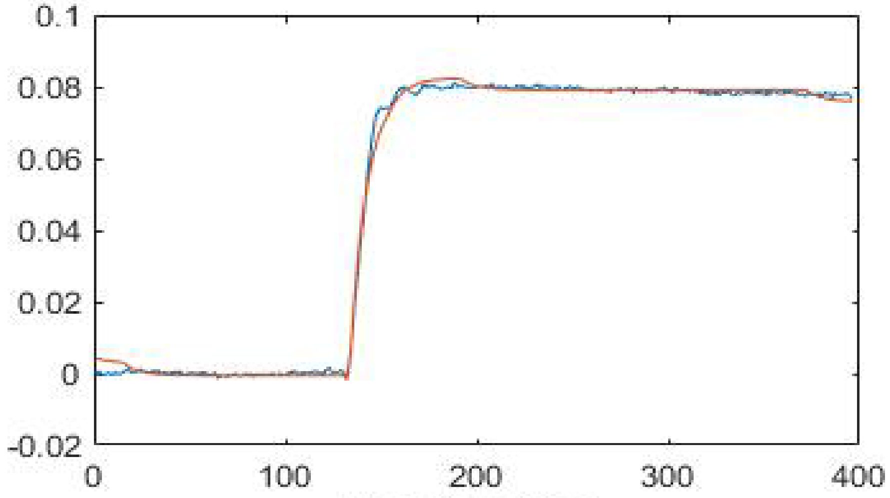


Turbine Complex

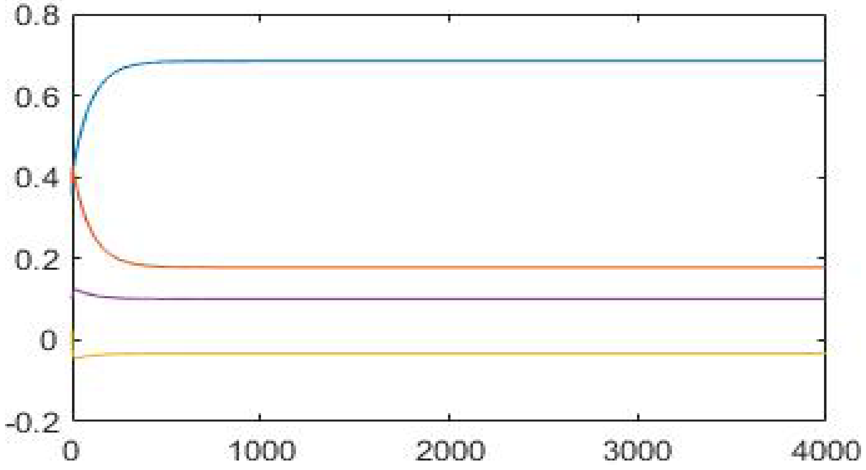
DT Learning Results



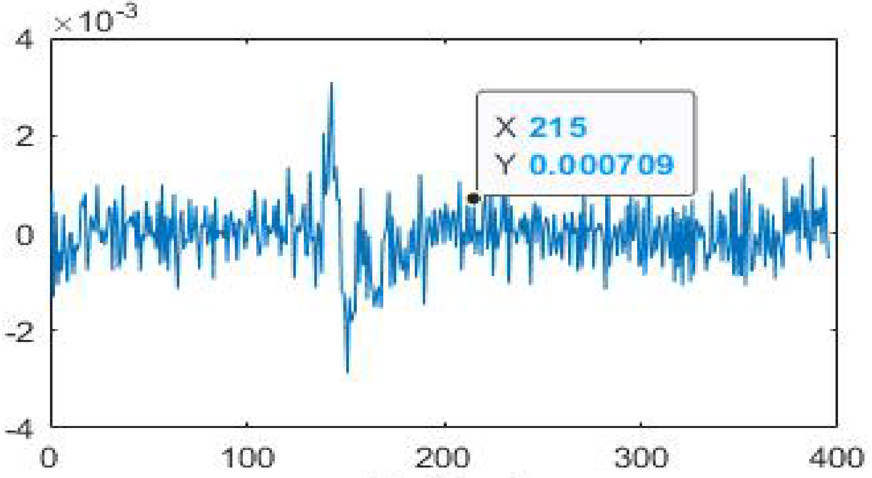
Normalized Data



Modeling effects

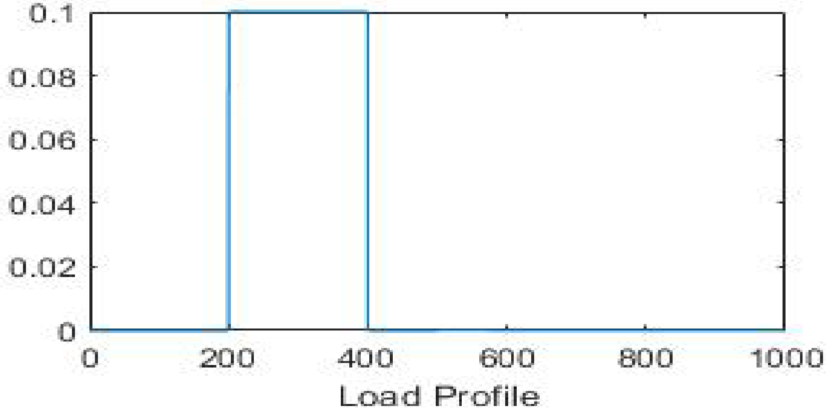


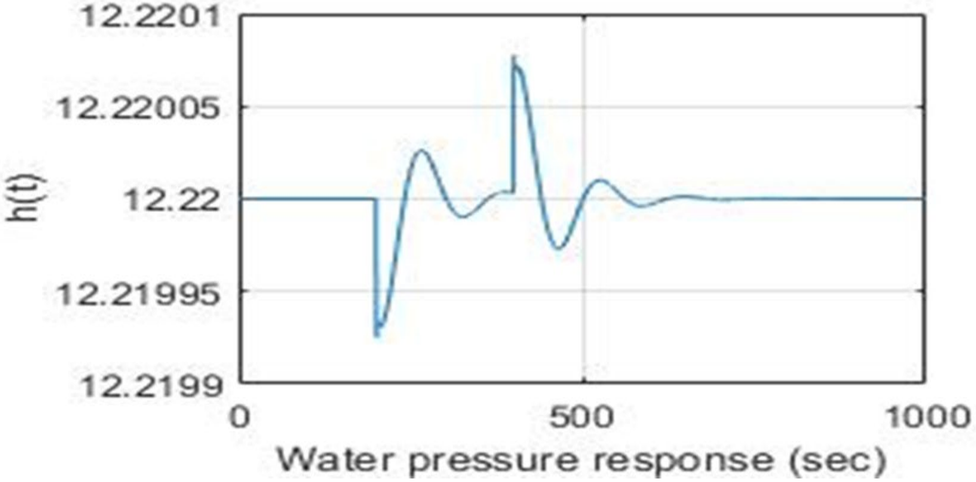
Estimated parameter responses in batch-by-batch index

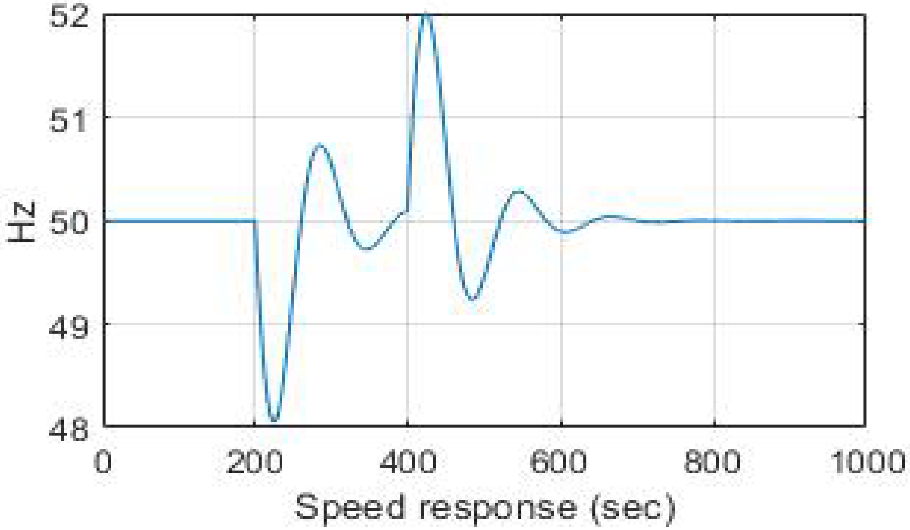


Residual

Power Generation Systems - Voltage Control Models and Load Dynamics

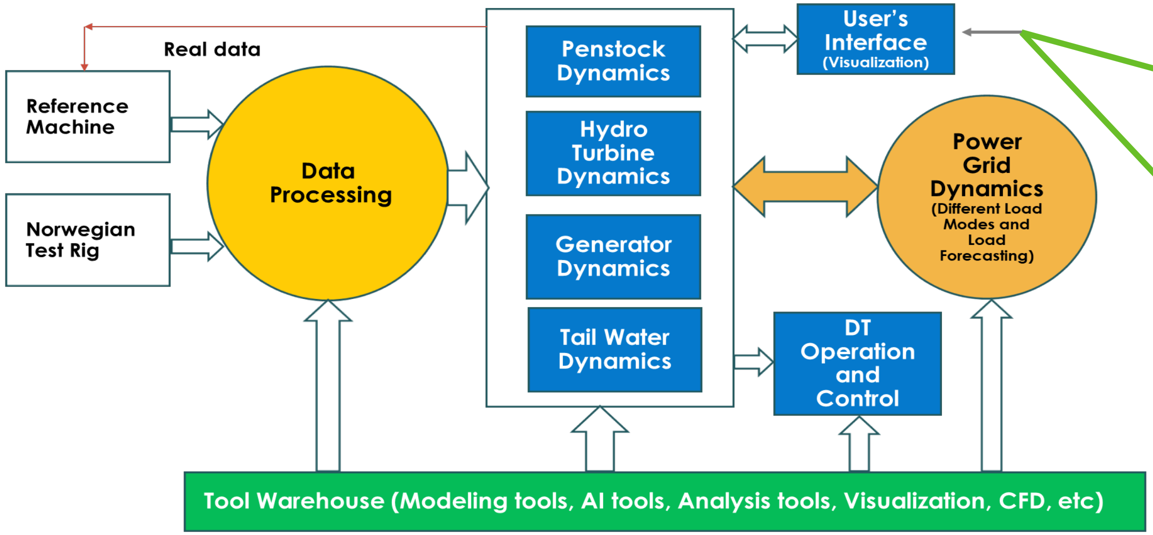






Load Profile - Frequency Regulation in [0, 500sec]

DT Model and Virtual Reality Display



Real data

Reference Machine

Norwegian Test Rig

Data Processing

Penstock Dynamics

Hydro Turbine Dynamics

Generator Dynamics

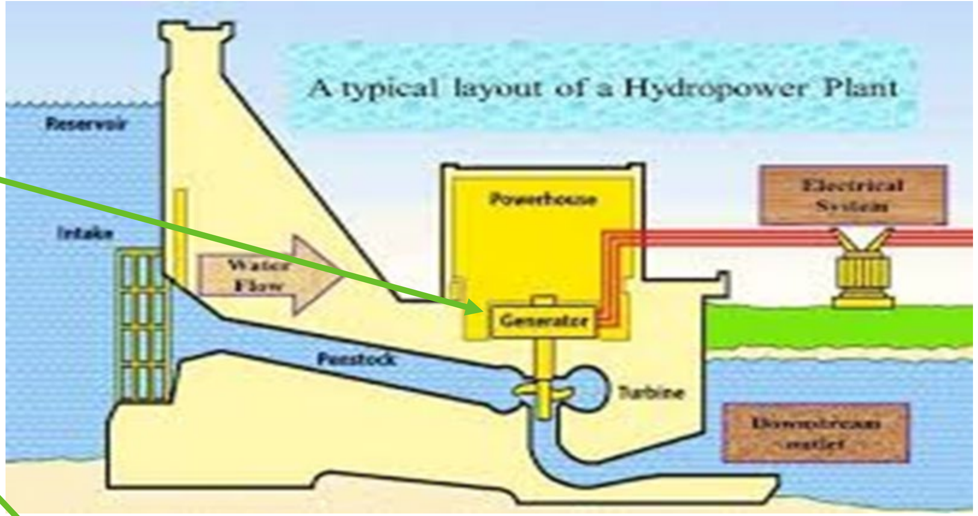
Tail Water Dynamics

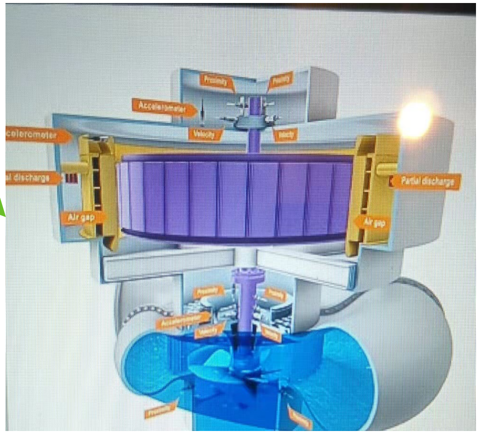
User's Interface (Visualization)

Power Grid Dynamics (Different Load Modes and Load Forecasting)

DT Operation and Control

Tool Warehouse (Modeling tools, AI tools, Analysis tools, Visualization, CFD, etc)





System Application Cases for DT

Plant Optimization

- Use DT as a platform to manipulate key decision variables (power generation, control parameters) to achieve the best and economic benefit for the grid operation in a large operational range

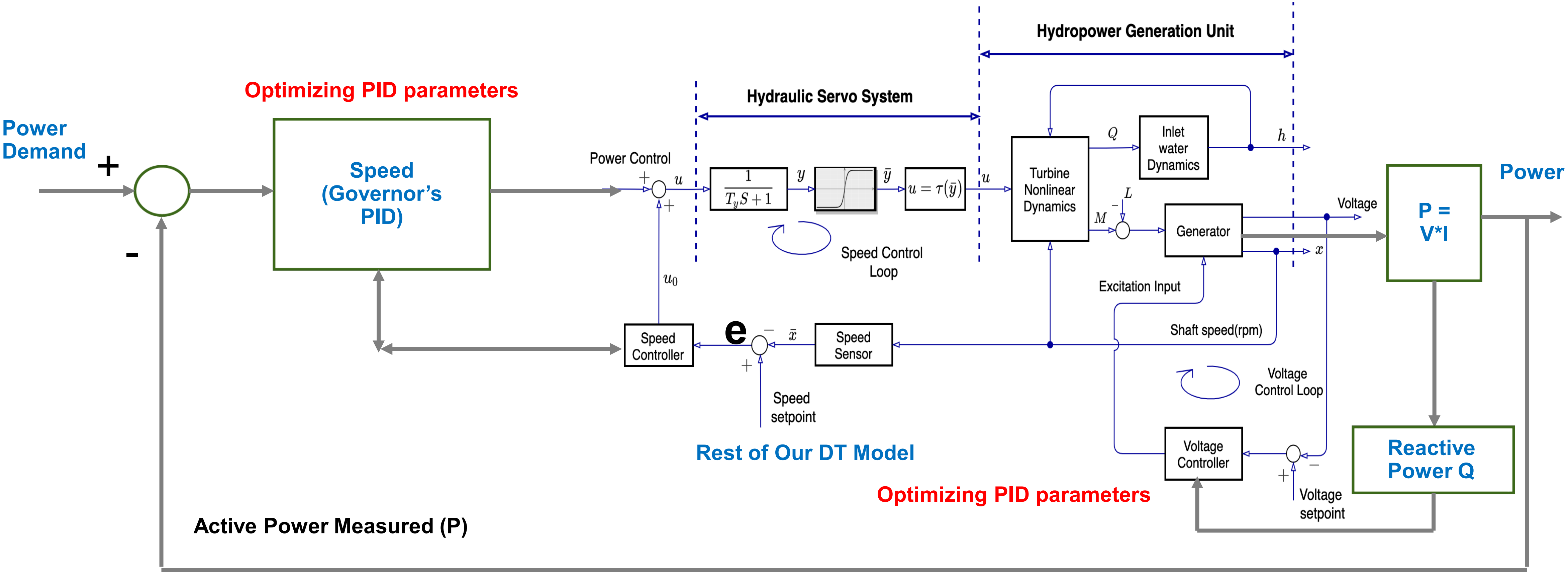
Smart Maintenance

- Use DT to simulation various faults in the system and then test and validation the smart maintenance plan that would lead to economic repairs, etc. for the hydropower systems

Operational Control Systems Optimization for Power Generation - Unit Level

Control the Power to Make Sure

1) Good tracking with respect to variable power demand from EMS
2) Make sure a minimized water pressure variations via smooth gate opening



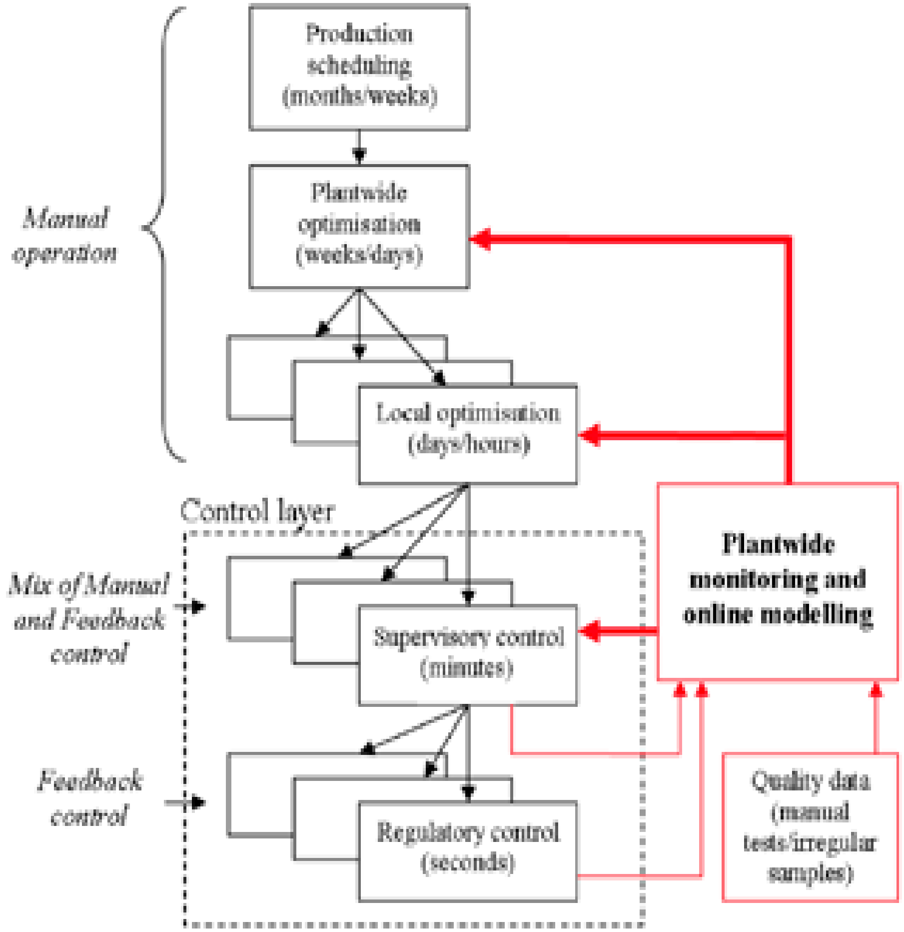
Smart Maintenance Systems for Hydropower

Purpose

1) Detect faults in the systems and perform fault diagnosis and prediction
2) Arrange economic repair and in the meantime realize fault tolerant control

DT can be Used in the Following Way

- ☐ Embed component and subsystem models in DT—temperature, bearing, vibration, etc.
- ☐ Generate fault scenarios and relevant data
- ☐ Perform fault detection, diagnosis, and prediction
- ☐ Schedule economic repairs or realizing fault tolerant control based upon the fault diagnosis



Conclusion and the Future

DT for hydropower systems is a key part in digitalization

  - It helps to optimize plant operation
  - It helps to obtain smart maintenance strategies

- It constitutes an important part for the whole grid operation when subjected to the increased penetration of renewables–wind, solar, etc.

Our Publications

[1] H Wang, O Ahmed, B Smith and B Bellgraph, Developing a digital twin for hydropower systems - an open platform framework, ***International Water Power & Dam Construction Magazine***, Vol. 75, July, 2021

[2] H Wang and S Ou, Structured Neural Network Modeling for Developing Digital Twins Models of Hydropower Generation Units, ***IEEE International Conference on Industrial Electronics and Applications***, Norway, 24, 2024

[3] Hong Wang, Shiqi (Shawn) Ou, Ole Gunnar Dahlhaug, Pål-Tore Storli, Hans Ivar Skjelbred and Ingrid Vilberg, Adaptively Learned Modeling for a Digital Twin of Hydropower Turbines with Application to a Pilot Testing System, ***Mathematics***, 2023

[4] H Wang, Z Yin and Z P Jiang, Real-time Hybrid Modeling of Francis Hydro-turbine Dynamics via a Neural Controlled Differential Equation Approach, ***IEEE Access***, 2024

[5] Z Yin, H Wang and Z Jiang, Parameter Estimation of Synchronous Generator Using Neural Controlled Differential Equations, ***IEEE Conference on Automation and Applications***, Iceland, 2024

[6] Hong Wang, Osman Ahmed, Ole Gunnar Dahlhaug, Pål-Tore Storli, Hans Ivar Skjelbred and Ingrid Vilberg, Adaptive hybrid 1D modeling for digital twin of hydropower systems, ***Proceedings of the 40th IAHR World Congress***, Vienna, 2023

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ENERGY

Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY

Digital Twin for Hydropower Systems: Scalable Infrastructure and Architecture

Chitra Sivaraman
Principal Investigator
Pacific Northwest National Laboratory

Pacific Northwest
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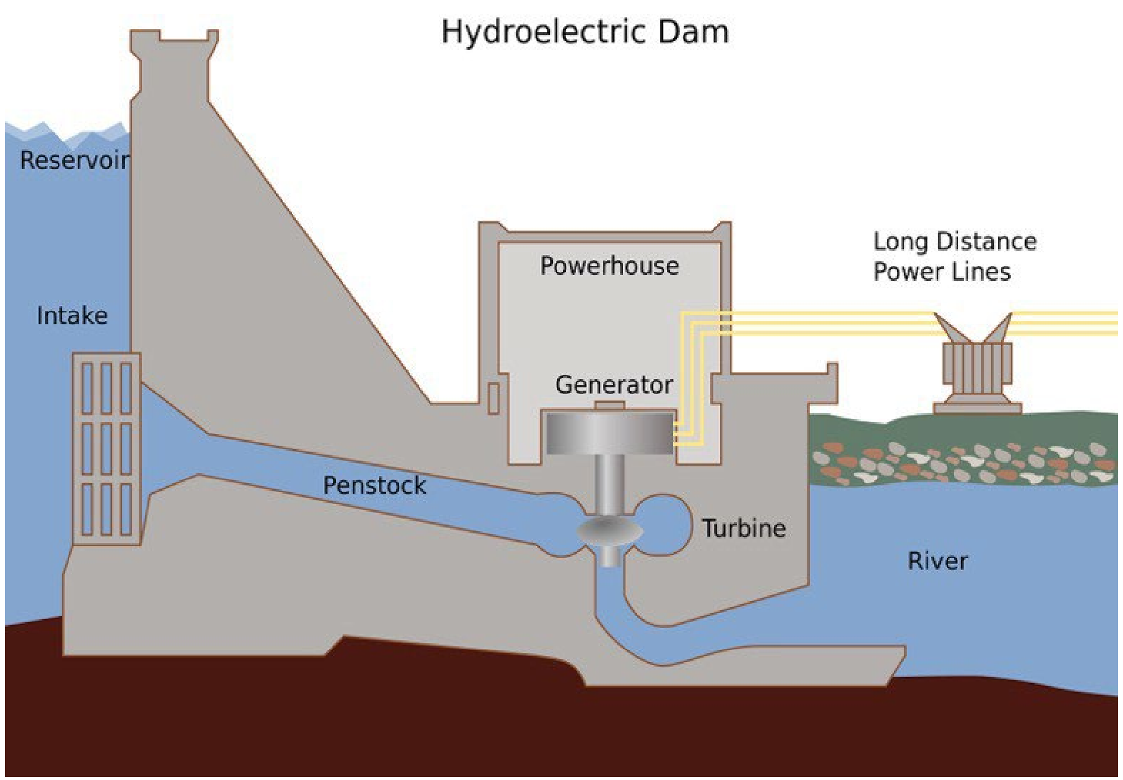
Hydropower – History and Statistics



Hydroelectric facility diagram by Energy Education

- Hydropower currently accounts for 28.7% of total U.S. renewable electricity generation and about 6.2% of total U.S. electricity generation.
- Hydropower also produces a number of benefits outside of electricity generation, such as flood control, irrigation support, and water supply.

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Types of Hydropower Turbines

Reaction vs Impulse Turbines

- The main difference between the impulse turbine and the reaction turbine.
- In impulse turbine, there is a pressure drop across the fixed blades only, whereas in the Reaction turbine, there is a pressure drop across both the fixed and the moving blades.

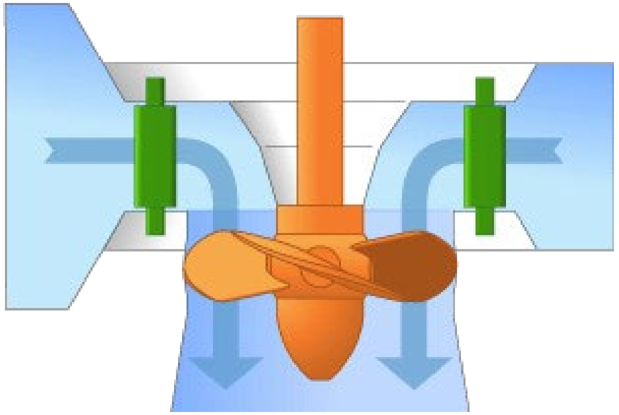
Some Types of Reaction Turbines

Kaplan Turbine

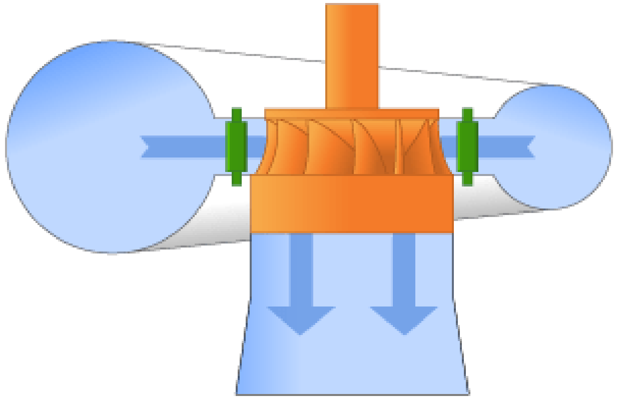
- Both the blades and the wicket gates are adjustable, allowing for a wider range of operation.

Francis Turbine

- Has a runner with fixed blades, usually nine or more. Water is introduced just above the runner and all around it which then falls through, causing the blades to spin. Besides the runner, the other major components include a scroll case, wicket gates, and a draft tube.



Kaplan Turbine



Francis Turbine

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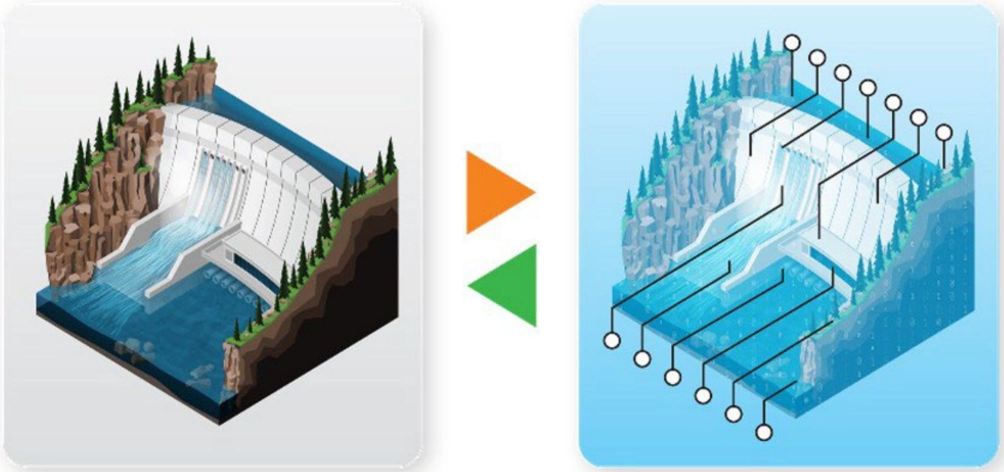
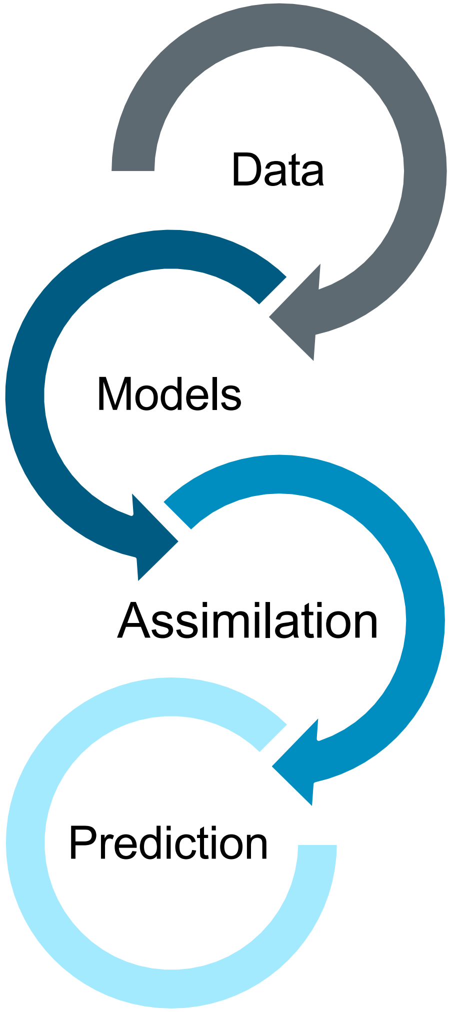
Digital Twin Dashboard for Hydropower Systems

Created using a physical and/or machine learning model assimilated with real-time data



A digital twin couples a real-world system—in this case a hydropower facility—with a virtual simulation to support optimization



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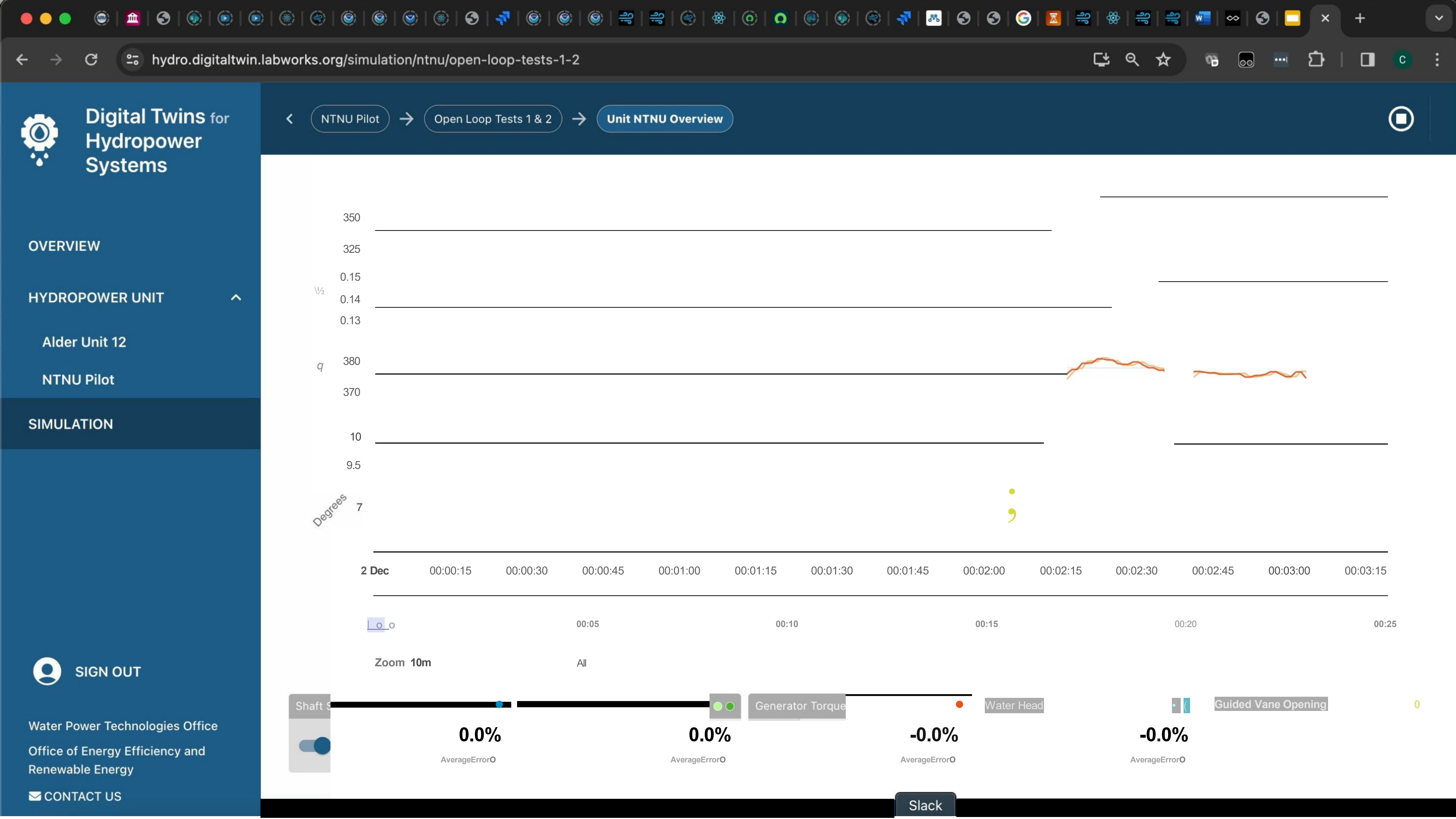
Compare Simulations with Real Data – Test Unit

Francis Test Rig at Norwegian University of Science and Technology

- Turbine speed: 0–744 rotations-per-minute
- Generator power: 400 kilowatts
- Generator voltage: 0–400 volts
- Generator current: 0–700 Amp


hydro.digitaltwin.labworks.org/simulation/ntnu/open-loop-tests-1-2
Digital Twins for Hydropower Systems
NTNU Pilot
Open Loop Tests 1 & 2
Unit NTNU Overview
OVERVIEW
HYDROPOWER UNIT
Alder Unit 12
NTNU Pilot
SIMULATION
SIGN OUT
Water Power Technologies Office
Office of Energy Efficiency and Renewable Energy
CONTACT US
350
325
0.15
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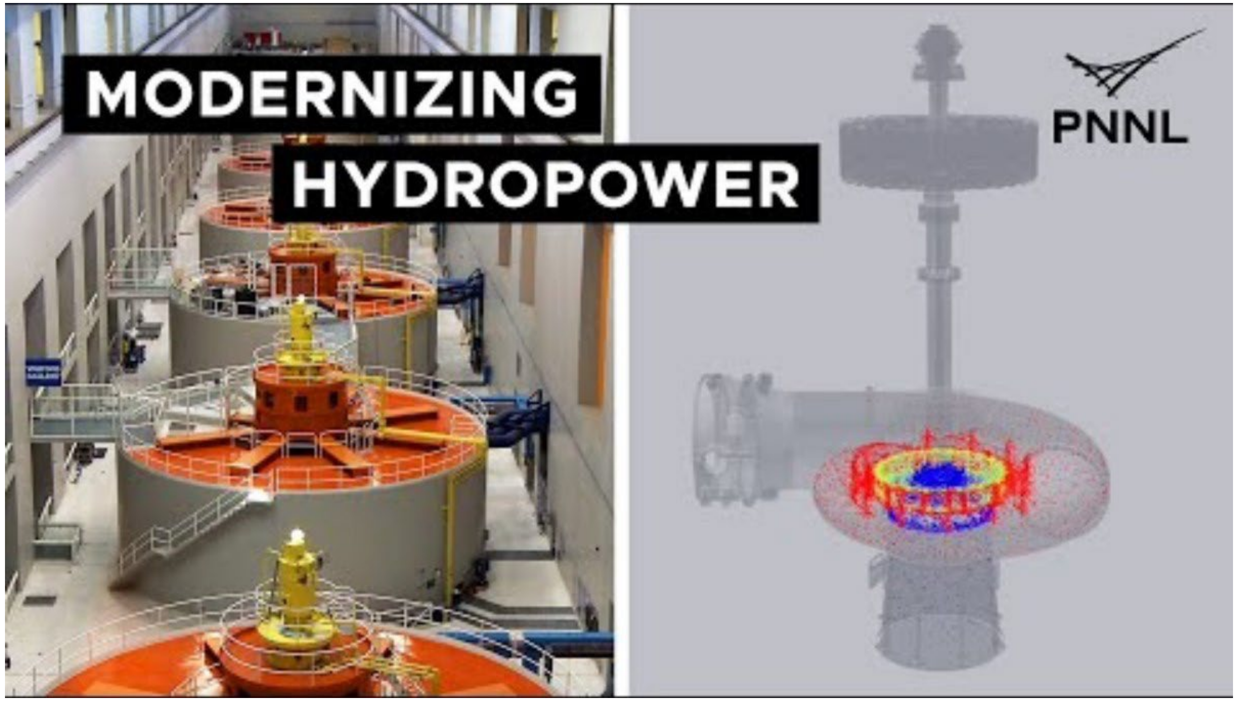
00:02:45
00:03:00
00:03:15
00:05
00:10
00:15
00:20
00:25
Zoom 10m
All
Shaft S
Generator Torque
Water Head
Guided Vane Opening
0
0.0%
AverageErrorO
0.0%
AverageErrorO
-0.0%
AverageErrorO
-0.0%
AverageErrorO
Slack

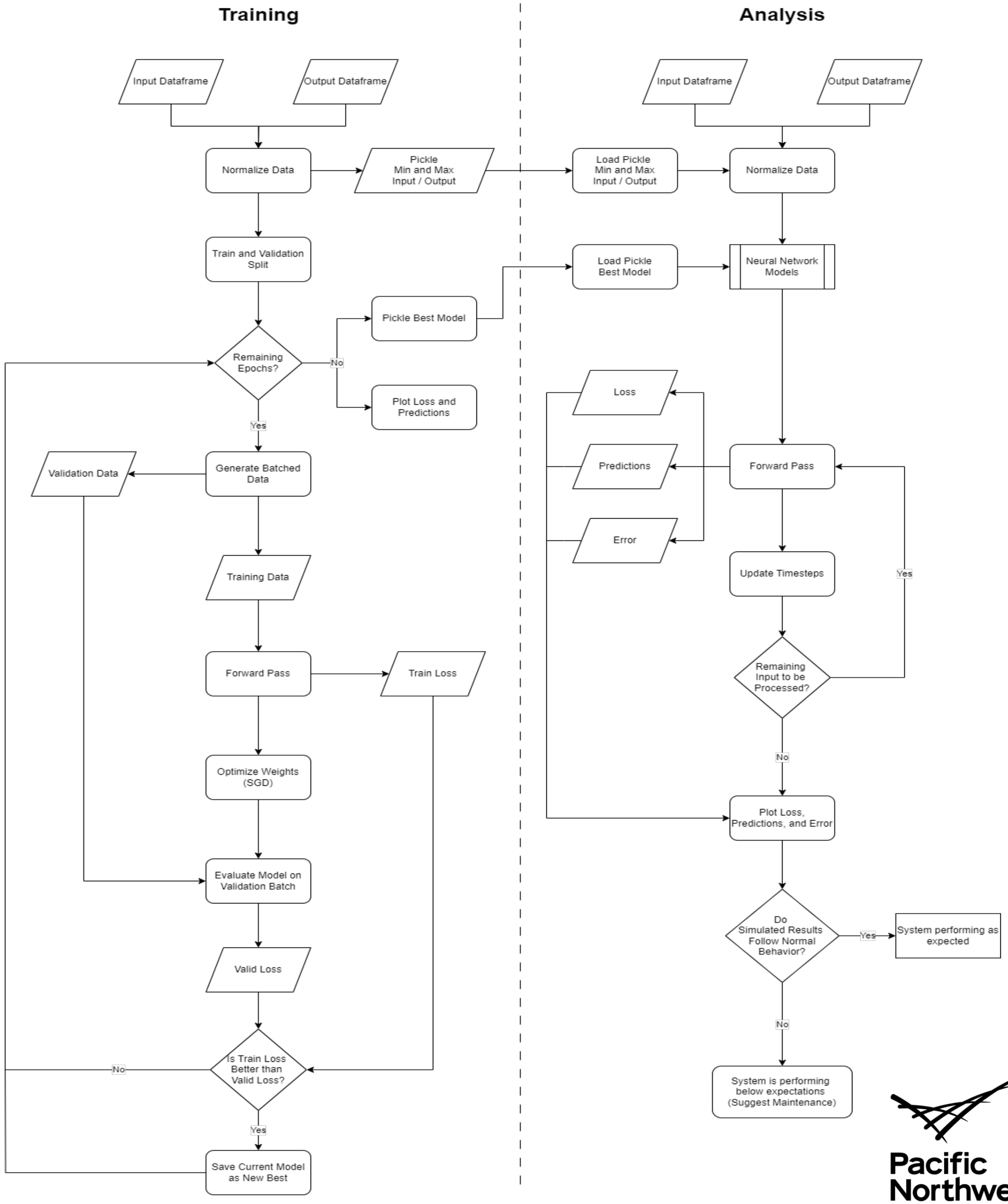
Alder Dam

- Water from Alder Lake is sent into two generators at the base of the dam
- 25 megawatts for a total nameplate capacity of 50 megawatts
- Rebuilt in 1945
- Serves 18,000 homes
- Francis turbine

https://www.mytpu.org/about-tpu/services/power/about-tacoma-power/dams-power-sources/nisqually-river-project/alder-dam/

Training and Analysis Flowchart





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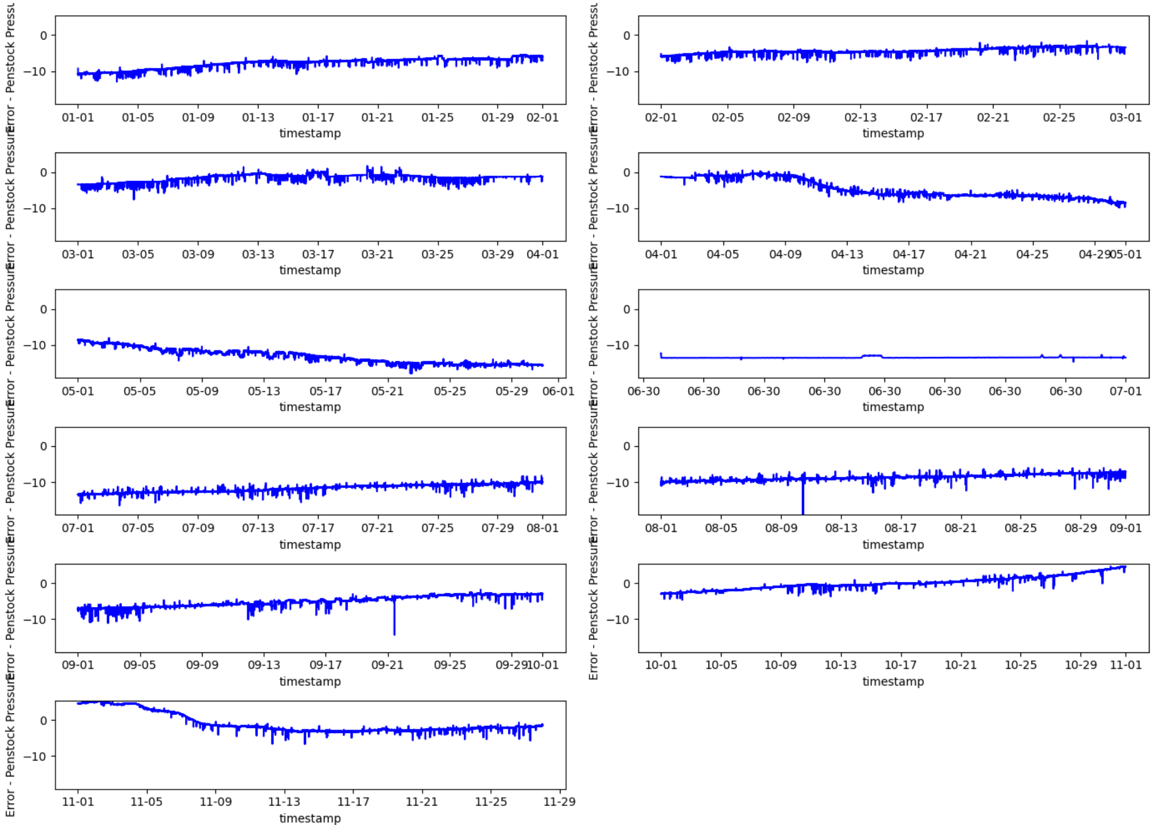
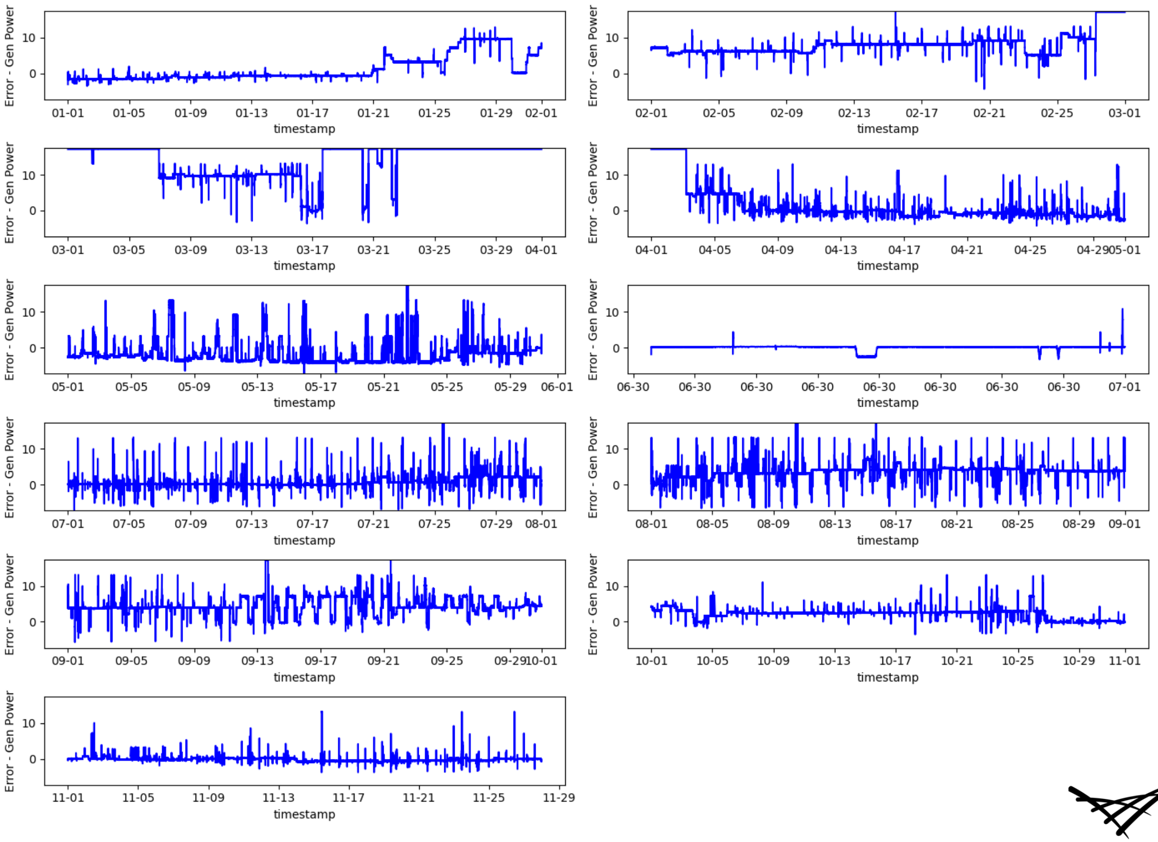
Validation Results for Five Years of Historical Data

Penstock pressure and generated power—difference between model and measured





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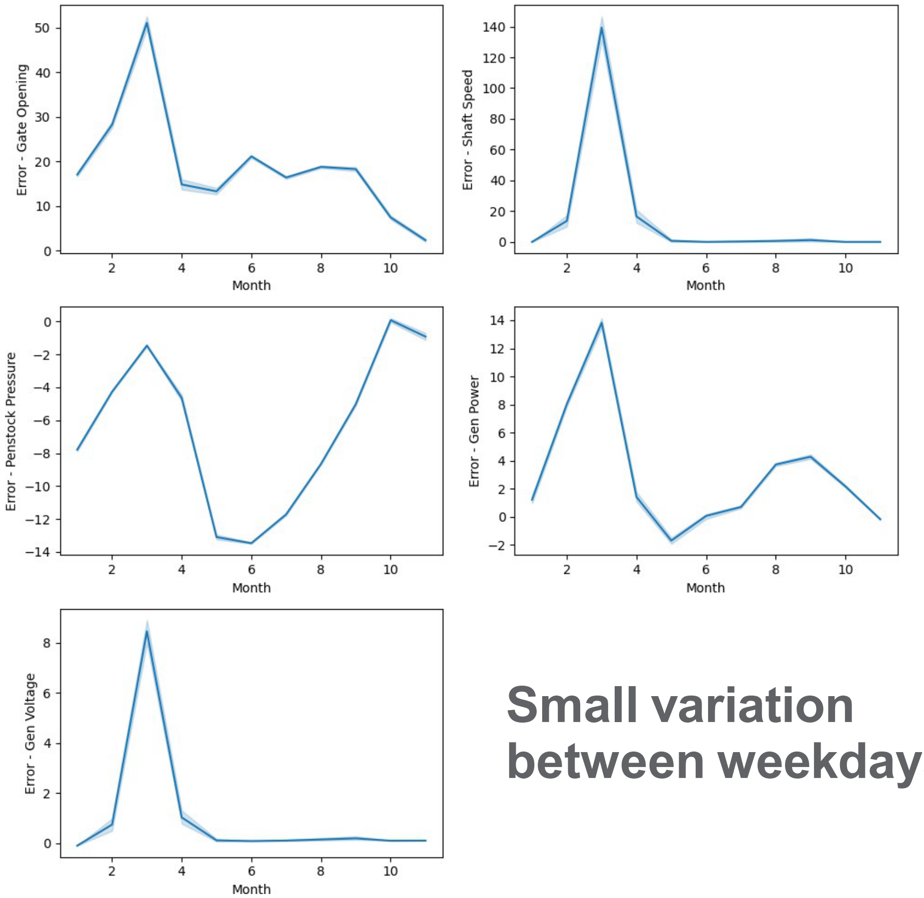
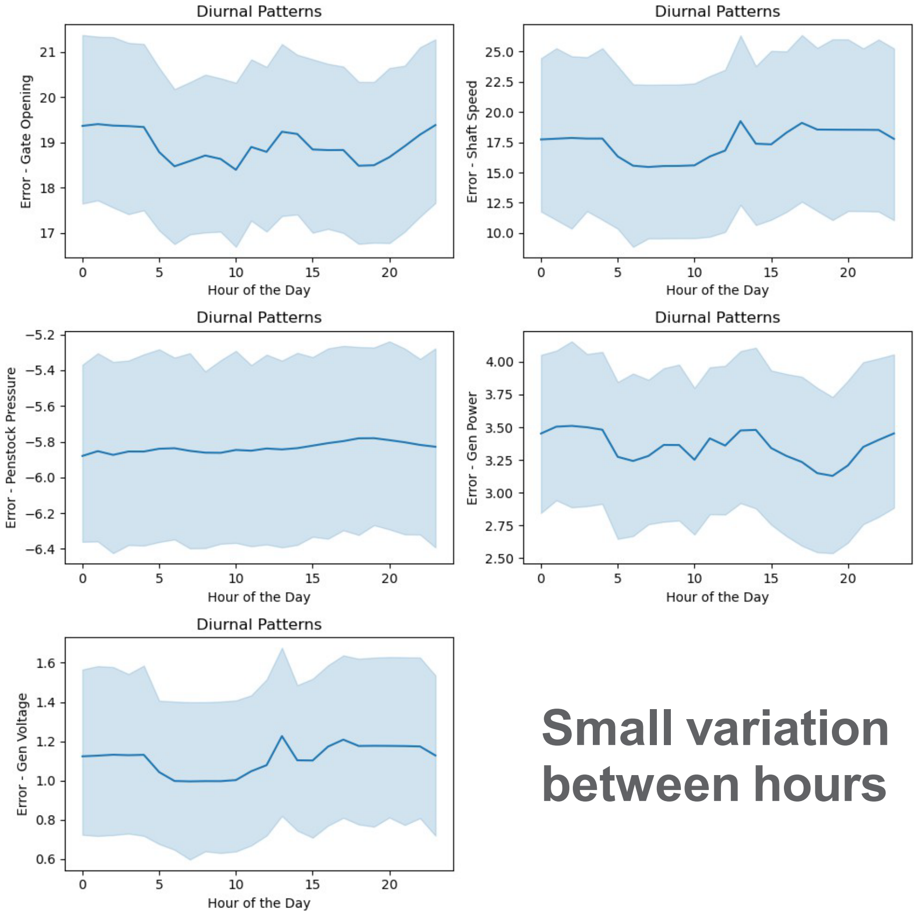
Seasonal and Diurnal Patterns



Small variation between weekdays



Small variation between hours

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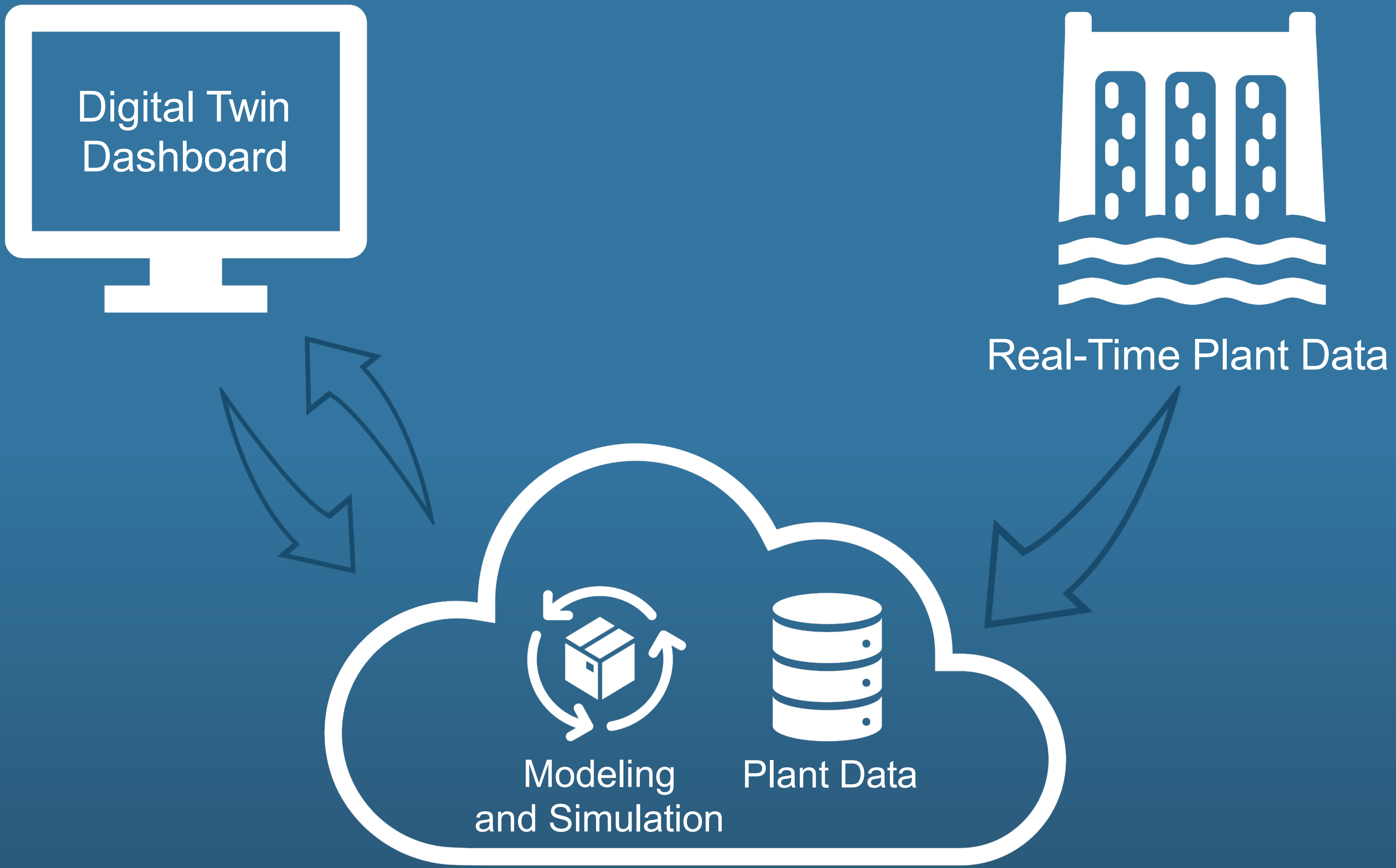
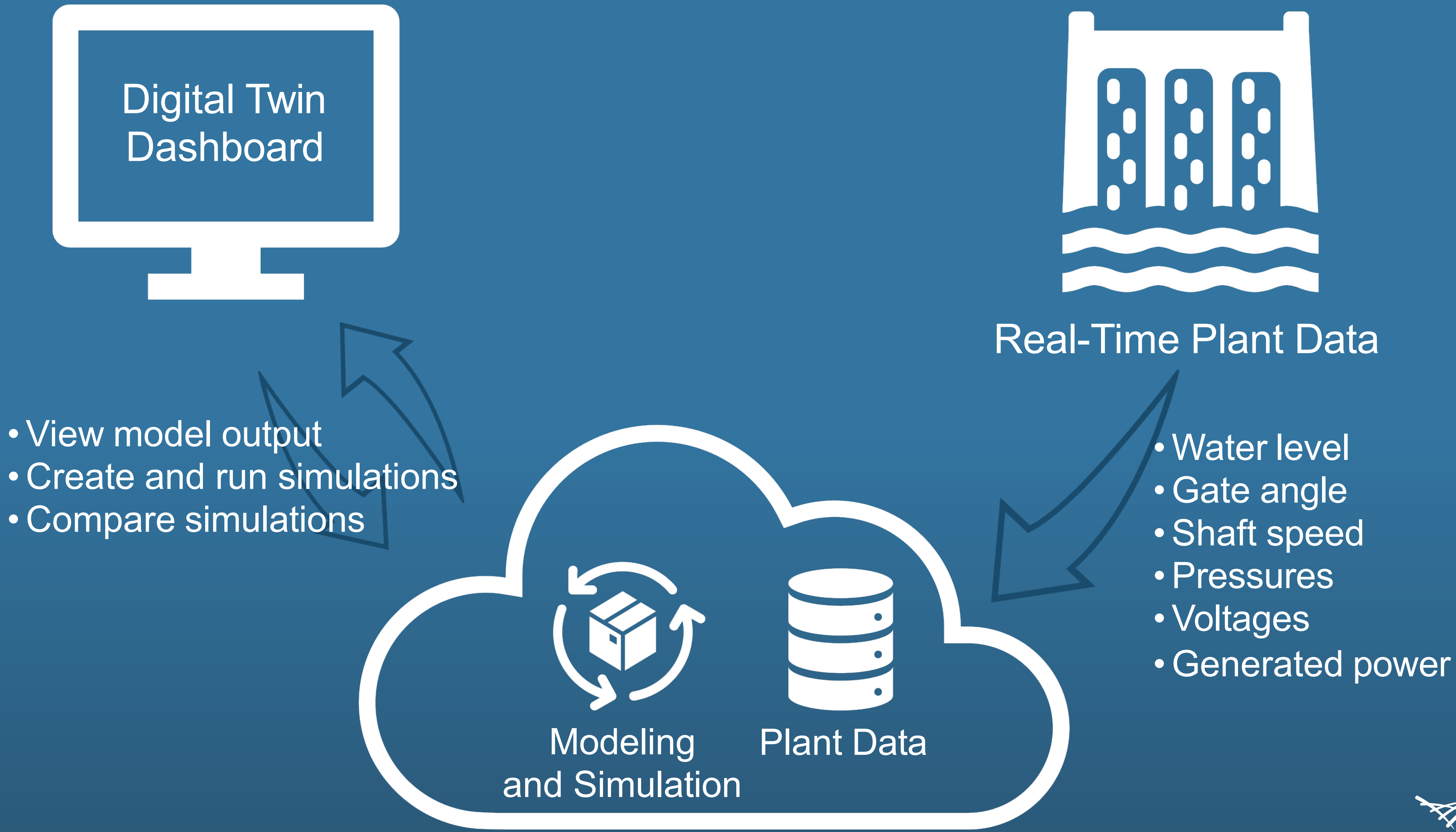


Digital Twin Dashboard

Real-Time Plant Data

Modeling and Simulation

Plant Data



Digital Twin Dashboard

- View model output
- Create and run simulations
- Compare simulations

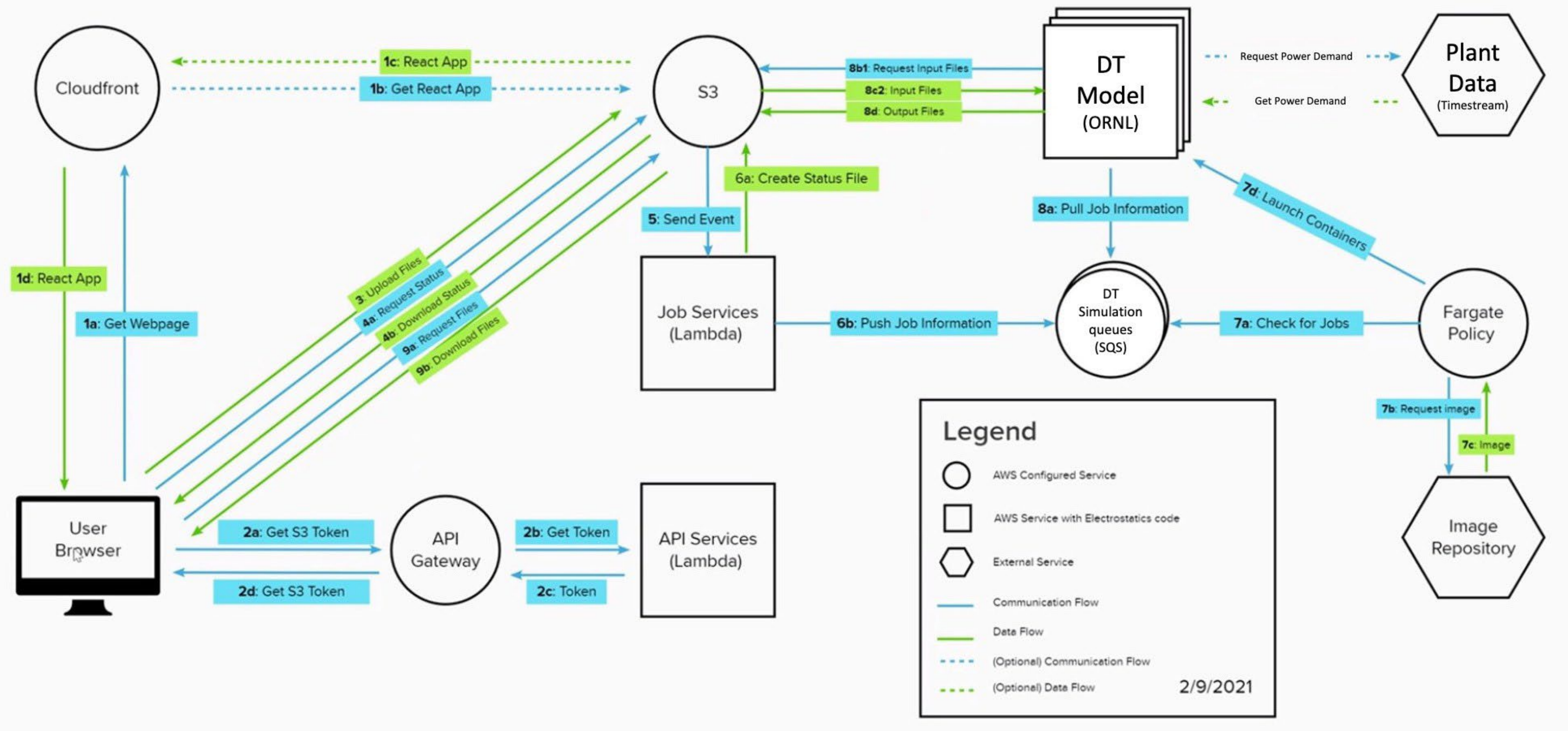
Real-Time Plant Data

- Water level
- Gate angle
- Shaft speed
- Pressures
- Voltages
- Generated power

Modeling and Simulation

Plant Data

Deployment of Digital Twin



2/9/2021

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Factors to Consider during Deployment of Digital Twin Dashboard

- Real-time data integration, potential online, and offline continual learning
- Access and security
- Human-machine interface design
- Interoperability of digital twins for turbines and other components
- Standardization of data
- Standard methods to transform input data
- Leveraging cloud base infrastructure and capabilities

Compare and View Scenarios

Start Date 2022 01 01

End Date 2023 08 30

Shaft Speed	Terminal Voltage	Pressure	Gate Opening	Power	Field Current	Field Voltage
-0.3%	29.5%	-0.4%	-7.6%	0.2%	—	—
Average Error	Average Error	Average Error	Average Error	Average Error		

- Run simulations
- Predict behavior
- Test changes
- Optimize performance

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Compare and View Scenarios (continued)

Simulations

	INPUTS						OUTPUTS				
	GOVENOR PI GAINS		VOLTAGE PI GAINS		POWER PI GAINS		FLOW VELOCITY	FLOW DISCHARGE	MASS FLOW RATE	POWER OUTPUT	EFFICIENCY
	K_p	K_i	K_p	K_i	K_p	K_i	ft/s	cu ft/s	lb/s	kW	
Low water simulation (Tacoma Facility) Created on July 22nd at 8:30am by Chitra S.	7.5	0.8	3.0	0.2	5.0	1.0	100	200,000	12,460,000	270,304	+2%
1/2 Operational sim (Tacoma Facility) Created on July 22nd at 8:30am by Chitra S.	3.2	0.4	1.5	0.1	2.5	0.5	50	97,000	4,350,00	231,201	-8%
High water simulation (Tacoma Facility) Created on July 22nd at 8:30am by Chitra S.	7.5	0.8	3.0	0.2	5.0	1.0	200	310,000	15,230,940	310,403	+8%
Seasonal simulation (Tacoma Facility) Created on July 22nd at 8:30am by Chitra S.	7.5	0.8	3.0	0.2	5.0	1.0	75	165,000	9,460,000	252,105	-4%
New Turbine simulation (Tacoma Facility) Created on July 22nd at 8:30am by Chitra S.	9.5	0.8	6.0	0.2	9.0	1.0	125	225,000	14,760,000	312,505	+9%

mand fluctuations

Predictive Analysis Uses Cases

Cooling water

- Pipes and filters clog or get blocked over time resulting in decreased flow and increased operation temps
- Results in decreased efficiency, shortened life of other components, callouts, etc.

Lube oil

- Critical auxiliary system, oil temperature, and flow protect bearings
- Leaks, high temperature, lack of flow could prevent costly failure

Additional Capabilities

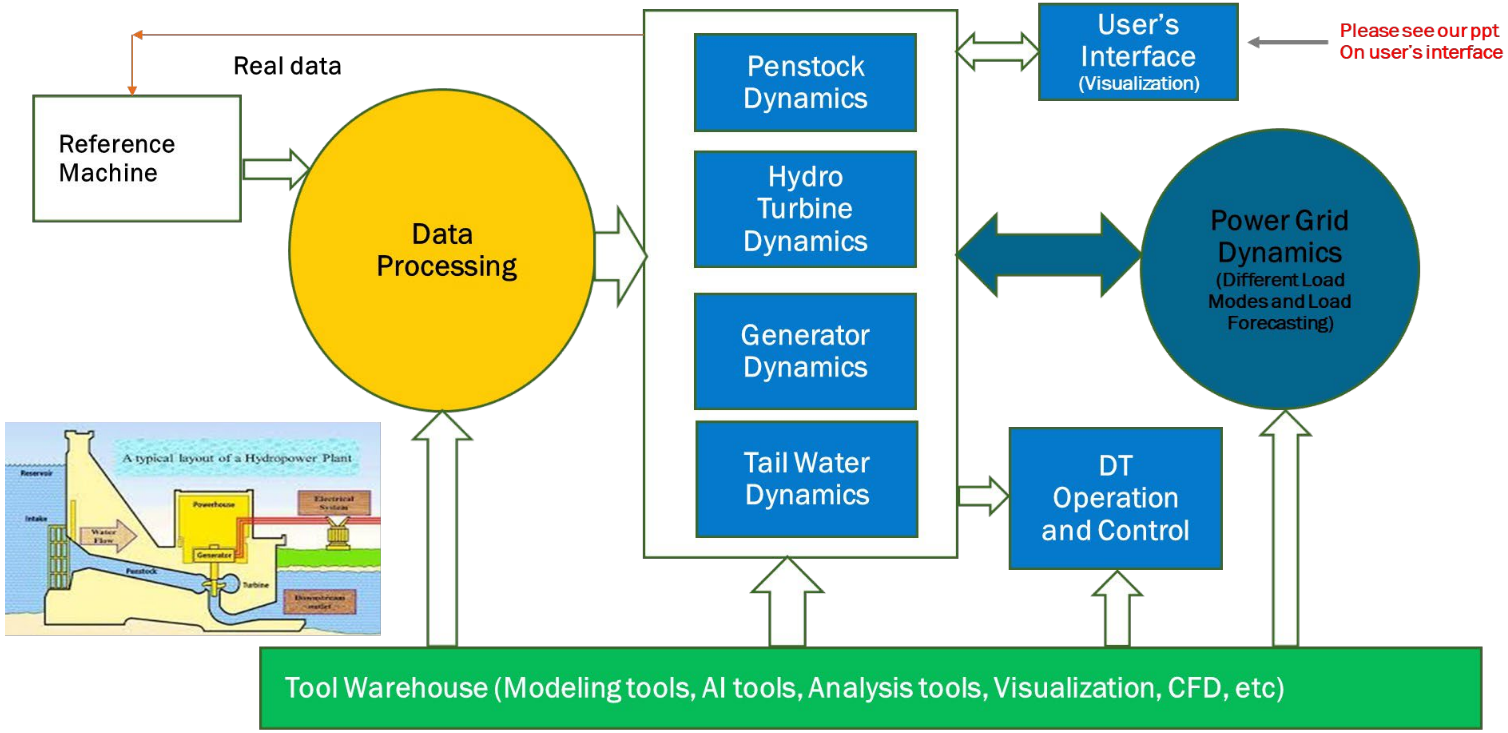
Extend to Other Models

- Environmental effects
- Seasonal reductions and fluctuations in pH
- Managing water flow during late summer
- Fish passage effects
- Many others

System Module Overview

Kaplan Turbine

- Wear and tear fatigue on the unit
- New source of data



Real data

Reference Machine

Data Processing

Penstock Dynamics

Hydro Turbine Dynamics

Generator Dynamics

Tail Water Dynamics

User's Interface (Visualization)

Please see our ppt On user's interface

Power Grid Dynamics (Different Load Modes and Load Forecasting)

DT Operation and Control

Tool Warehouse (Modeling tools, AI tools, Analysis tools, Visualization, CFD, etc)

Contact Us

To learn more and access the Digital Twin dashboard, scan the QR code or visit hydro.digitaltwin.labworks.org

For more information, email the team at digitaltwinhydro@pnnl.gov

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Barriers and Challenges to Implementing Digital Twins

5

Moderator: **Vaibhav Yadav,** Idaho National Laboratory
Joshua New, Oak Ridge National Laboratory
Carrie Dossick, University of Washington
Carolina Cruz-Neira, University of Central Florida
Parastoo Delgoshaei, National Institute of Standards and Technology

Automatic Building Energy Modeling (AutoBEM) and its Model America dataset

For: Opportunities for Digital Twins in the Built Environment

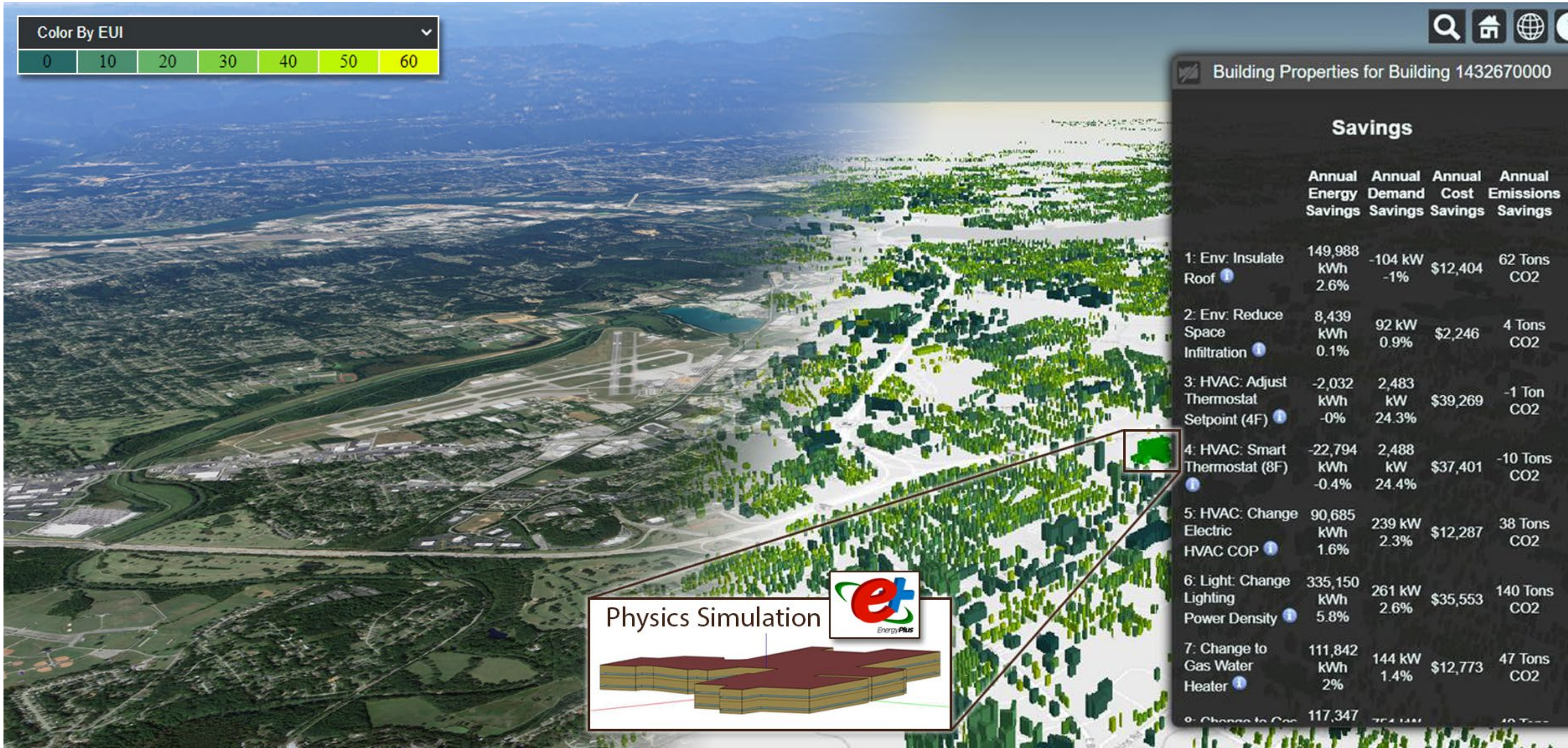
Presented by:
Joshua New, Ph.D., C.E.M., PMP, CMVP, CSM, IREE
Distinguished R&D Staff Member, Oak Ridge National Laboratory

Date: 6/13/24

ORNL is managed by UT-Battelle LLC for the US Department of Energy

Results (Data+Models – bit.ly/ModelAmerica1; Publications – bit.ly/AutoBEM)

- Digital twin of every U.S. building (125.7M data, 122.9M models; 141.5M in version2)
  - Estimates energy (kBtu), demand (kW), emissions ($CO_{2\text{-eq}}$) and cost ($) savings



Building Properties for Building 1432670000

Savings

	Annual Energy Savings	Annual Demand Savings	Annual Cost Savings	Annual Emissions Savings
1: Env: Insulate Roof	149,988 kWh 2.6%	-104 kW -1%	$12,404	62 Tons CO2
2: Env: Reduce Space Infiltration	8,439 kWh 0.1%	92 kW 0.9%	$2,246	4 Tons CO2
3: HVAC: Adjust Thermostat Setpoint (4F)	-2,032 kWh -0%	2,483 kW 24.3%	$39,269	-1 Ton CO2
4: HVAC: Smart Thermostat (8F)	-22,794 kWh -0.4%	2,488 kW 24.4%	$37,401	-10 Tons CO2
5: HVAC: Change Electric HVAC COP	90,685 kWh 1.6%	239 kW 2.3%	$12,287	38 Tons CO2
6: Light: Change Lighting Power Density	335,150 kWh 5.8%	261 kW 2.6%	$35,553	140 Tons CO2
7: Change to Gas Water Heater	111,842 kWh 2%	144 kW 1.4%	$12,773	47 Tons CO2
	117,347			

Automatic Building Energy Modeling (AutoBEM) - Chattanooga

- Validation
  - 15-Minute electricity use
  - 178,000 building electrical meters
  - Chattanooga, TN
- Technological Evolution
  - Data
  - Algorithms
- Analysis
  - Energy saving technologies
  - Demand saving technologies
  - Renewable technologies
  - Microgrids
- AutoBEM ingests known building properties (user input or database) automatically

Building Properties for Building 2659310000

Num Floors	7
Square Footage	1,648,094
Annual Energy Usage	13,069,609 kWh
Annual Aggregated Demand	27,260 kW
EUI	8 kWh/ft^2
CO2 emissions	12,968,594 lbs
Estimated wholesale vs retail cost	671,125 $

Savings

	Annual Energy Savings	Annual Demand Savings	Annual Cost Savings
1: Env: Insulate Roof	425,721 kWh 3.3%	1,402 kW 5.1%	$62,161
2: Env: Reduce Space Infiltration	100,741 kWh 0.8%	691 kW 2.5%	$20,418
3: HVAC: Adjust Thermostat Setpoint (4F)	23,547 kWh 0.2%	12,089 kW 44.3%	$194,305
4: HVAC: Smart Thermostat (8F)	-28,720 kWh -0.2%	12,113 kW 44.4%	$189,788
5: HVAC: Change Electric HVAC COP	119,645 kWh 0.9%	347 kW 1.3%	$16,727
6: Light: Change Lighting Power Density	706,276 kWh 5.4%	848 kW 3.1%	$79,657
7: Change to Gas Water Heater	151,892 kWh 1.2%	241 kW 0.9%	$18,063
8: Change to Gas HVAC	145,468 kWh 1.1%	967 kW 3.5%	$28,994
9: Combined Electric* Savings Potential (1,2,5,6)	1,352,383 kWh 10.3%	3,288 kW 12.1%	$178,963
10: Combined Demand* Savings Potential (4,7,8)	268,640 kWh 2.1%	13,321 kW 48.9%	$236,844

Digital Twin of Chattanooga, TN, shows energy, demand, emissions, and cost savings of individual measures and packages of energy efficient or demand response measures.

Climate change impacts to buildings – Arizona

- Phoenix, AZ – potential 5°F increase in 2100, 16% more electricity use, and 23% more demand

bit.ly/virtual_phoenix

8559FW99+VF7-3-2-2-2

Building Data

UBID	8559FW99+VF7-3-2-2-2
Building Type	SINGLE FAMILY RESIDENTIAL
Year Built	1949
Num Floors	1
Square Footage	2,477
Height (ft)	12

Total Energy Projections

	Annual Energy	Annual Cost	Annual Emissions
TMY3	58,234 kBTU	21,647 $	6.2 Tons CO2
fTMY 2020-2040	56,276 kBTU	20,942 $	6 Tons CO2
fTMY 2040-2060	58,949 kBTU	22,178 $	6.3 Tons CO2
fTMY 2060-2080	59,629 kBTU	22,706 $	6.4 Tons CO2
fTMY 2080-2100	63,832 kBTU	24,699 $	6.8 Tons CO2

Electricity Projections

	Annual Energy	Annual Cost	Annual Emissions
TMY3	47,950 kBTU	21,482 $	5.1 Tons CO2
fTMY 2020-2040	46,391 kBTU	20,783 $	5 Tons CO2
fTMY 2040-2060	49,154 kBTU	22,021 $	5.3 Tons CO2
fTMY 2060-2080	50,349	22,556 $	5.4 Tons

Scenario	Average Dry Bulb Temperature (°F)
TMY	23.8
fTMY 2020-2040	24.1
fTMY 2040-2060	25.8
fTMY 2060-2080	26.6
fTMY 2080-2100	29.1

Scenario	Total Energy	Electricity	Natural Gas
TMY	0.24 Quads	0.20 Quads	0.04 Quads
fTMY 2020-2040	-1.0%	-1.0%	-1.1%
fTMY 2040-2060	3.4%	4.6%	-3.2%
fTMY 2060-2080	4.6%	6.9%	-8.1%
fTMY 2080-2100	11.6%	15.9%	-12.3%

Scenario	Total Costs	Total Emissions
TMY	$ 8.5 Billion	26 Million Tons CO2
fTMY 2020-2040	-1.0%	-1.0%
fTMY 2040-2060	4.0%	3.4%
fTMY 2060-2080	5.85%	4.6%
fTMY 2080-2100	14.0%	11.6%

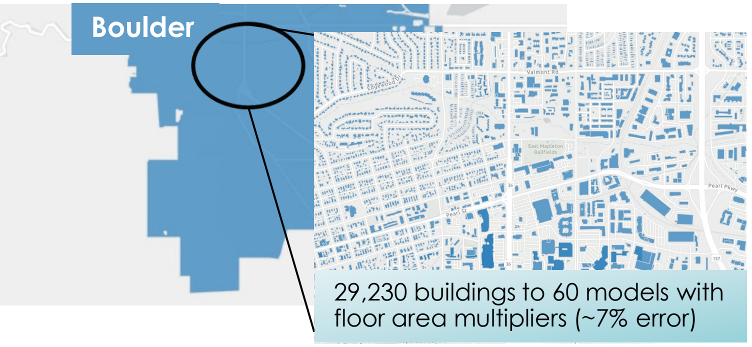
Scenario	July Total Energy
TMY	0.02 Quads
fTMY 2020-2040	1.9%
fTMY 2040-2060	11.1%
fTMY 2060-2080	14.3%
fTMY 2080-2100	23.0%

Hourly, county-specific climate change data 1980-2100 – bit.ly/fTMY

Analysis (2 years: 50+ NDAs, 13 projects supporting industry)

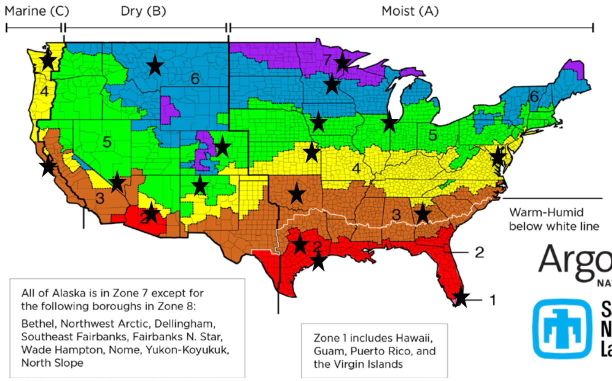
Supercomputing for building analysis (1M bldgs/hr)

Dynamic archetypes for area representation



29,230 buildings to 60 models with floor area multipliers (~7% error)

Climate Change – IPCC weather files for buildings



All of Alaska is in Zone 7 except for the following boroughs in Zone 8:
Bethel, Northwest Arctic, Dellingham, Southeast Fairbanks, Fairbanks N. Star, Wade Hampton, Nome, Yukon-Koyukuk, North Slope

Zone 1 includes Hawaii, Guam, Puerto Rico, and the Virgin Islands

Argonne NATIONAL LABORATORY

Sandia National Laboratories

AI for real-time EUI during building design

Climate Zone: 4B
Building Type: Large Office
Total Area: 140000
Target Floor Area: 20000
Plate Depth: 90
Floor-Floor Height: 10
WWR: 40
Solar Design: Good
Envelope Qual
HVAC Setting: Baseline
HVAC Setpoint: Baseline
LPD Setting: Baseline (100%)

EUI : 72.82 kBTU/sf
Cooling : 1.13 kBTU/sf
Heating : 40.47 kBTU/sf
Lighting : 14.48 kBTU/sf
Equipment : 30.13 kBTU/sf
Fans : 1.15 kBTU/sf
Pumps : 1.42 kBTU/sf
HeatRejection : 0 kBTU/sf
HeatRecovery : 0.29 kBTU/sf

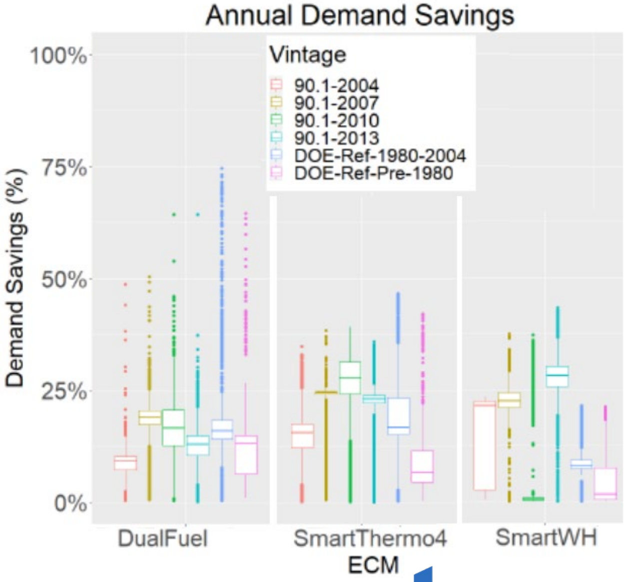
EUI : 72.82 kBTU/sf

$6.4B and 20,500 person-years of work in 1 hour

SMITHGROUP

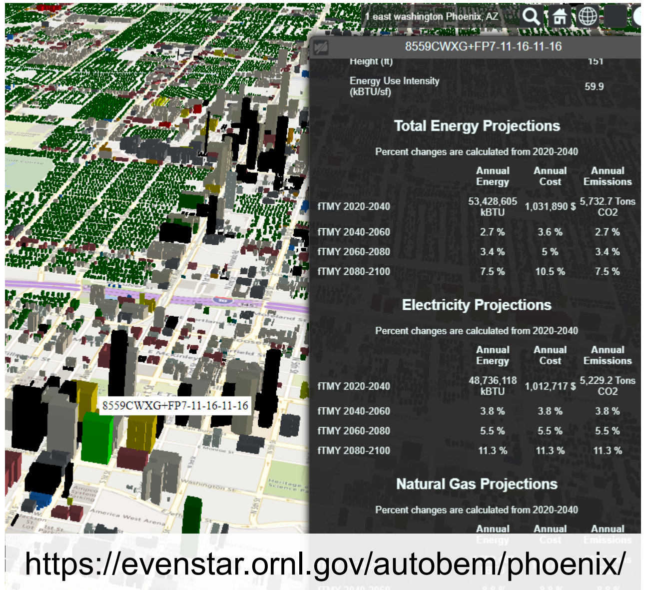
OAK RIDGE National Laboratory

Utility-scale savings used operationally



epb

Web-based visualization of climate change impacts



8559CWXG+FP7-11-16-11-16

Height (ft) 151

Energy Use Intensity (kBTU/sf) 59.9

Total Energy Projections

Percent changes are calculated from 2020-2040

	Annual Energy	Annual Cost	Annual Emissions
fTMY 2020-2040	53,428,605 kBTU	1,031,890 $	5,732.7 Tons CO2
fTMY 2040-2060	2.7 %	3.6 %	2.7 %
fTMY 2060-2080	3.4 %	5 %	3.4 %
fTMY 2080-2100	7.5 %	10.5 %	7.5 %

Electricity Projections

Percent changes are calculated from 2020-2040

	Annual Energy	Annual Cost	Annual Emissions
fTMY 2020-2040	48,736,118 kBTU	1,012,717 $	5,229.2 Tons CO2
fTMY 2040-2060	3.8 %	3.8 %	3.8 %
fTMY 2060-2080	5.5 %	5.5 %	5.5 %
fTMY 2080-2100	11.3 %	11.3 %	11.3 %

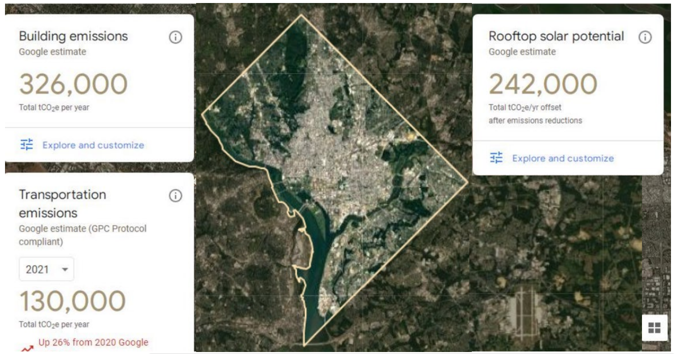
Natural Gas Projections

Percent changes are calculated from 2020-2040

https://evenstar.ornl.gov/autobem/phoenix/

LIGHTBOX

Buildings carbon footprint for 40,000 cities



Building emissions
Google estimate
326,000
Total tCO₂e per year

Rooftop solar potential
Google estimate
242,000
Total tCO₂e/yr offset
after emissions reductions

Transportation emissions
Google estimate (GPC Protocol compliant)
2021
130,000
Total tCO₂e per year
Up 26% from 2020 Google

	DC		
	Electricity	Natural Gas	Total
EIE	-44%	-73%	-46%
AutoBEM	-9%	23%	5%

Error <5% at city-scale

Google

New Work in the Digital Age

Dr. Carrie Sturts Dossick, P.E.

Dan Dimitrov, Ph.D. Candidate

Andrew Steele, MS Construction Management

NATION
ACADEM

Iot & Digital Twin Study (Dimitrov and Dossick)

Paradigm Shift in FM Industry

- Professionalizing Operations
  - Skillset shifts to enter the industry
    - Technician →Systems Engineer, Operation Technology Engineer
  - Interdisciplinary collaboration + centralization → FM no longer isolated practice

1. Breakdown Disciplinary Silos

2. Leadership in Technological Transformation

3. Challenge Cultural Norms + Entrenched Organizational Practices

4. Bridging the Gap- New Knowledge and Existing Knowledge

CSF CAMPUS SUSTAINABILITY FUND
csf.washington.edu

IoT in FM Cost Framework

(Steele and Dossick)

Key Themes from Interviews

Data Management:

“Managing and storing data is a substantial expense. If you do not have a data scientist or data analytics either outsourced or full-time, you will fail as a business.” (R2)

Cyber Security

“Cybersecurity is the number one concern.” (R1)

“The hidden cost of BAS is cybersecurity, which requires substantial investment to prevent costly attacks.” (R7)

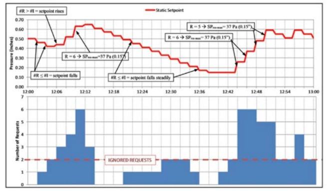
“Municipalities and organizations have paid substantial amounts to hackers due to data breaches.” (R6)

Building Digital Twins Layers and Slices

Standard Layers

Application Analytics Layer

ASHRAE Guideline 36, Std. 231P, 62.1

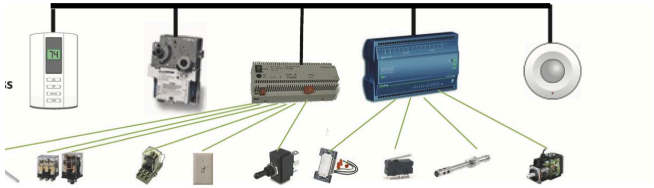


Building Systems Layer

ASHRAE 223P, ASHRAE 205

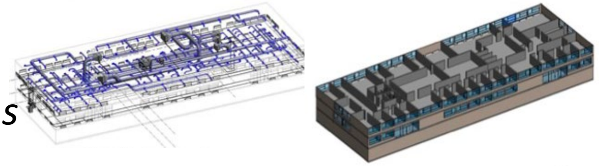
Communication Layer

BACnet, Modbus



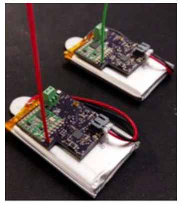
Structural Layer

BIM, Building Codes, Regulations



Data Layer

GIS, ISO, Metadata



Database

Contributing Emerging Technologies

Digital Twin

Augmented and Virtual Reality
- Privacy & Data Protection
- Safety & Liability
- Content Regulation

IoT Sensors
- Security
- Privacy
- Semantic Interoperability

AI
- Trustworthiness
- Governance

Cloud Computing
- Security

Cyber-Physical Systems
- Security
- Interoperability

Advanced Simulation & Modeling
- Representation and Data Exchange

NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
U.S. DEPARTMENT OF COMMERCE

Board Member Discussion

6

Mike Lamach, representing BEES (prerecorded video)
Omar Ghattas of UT Austin, representing CATS/BMSA
Jack Dempsey of AMP, representing BICE

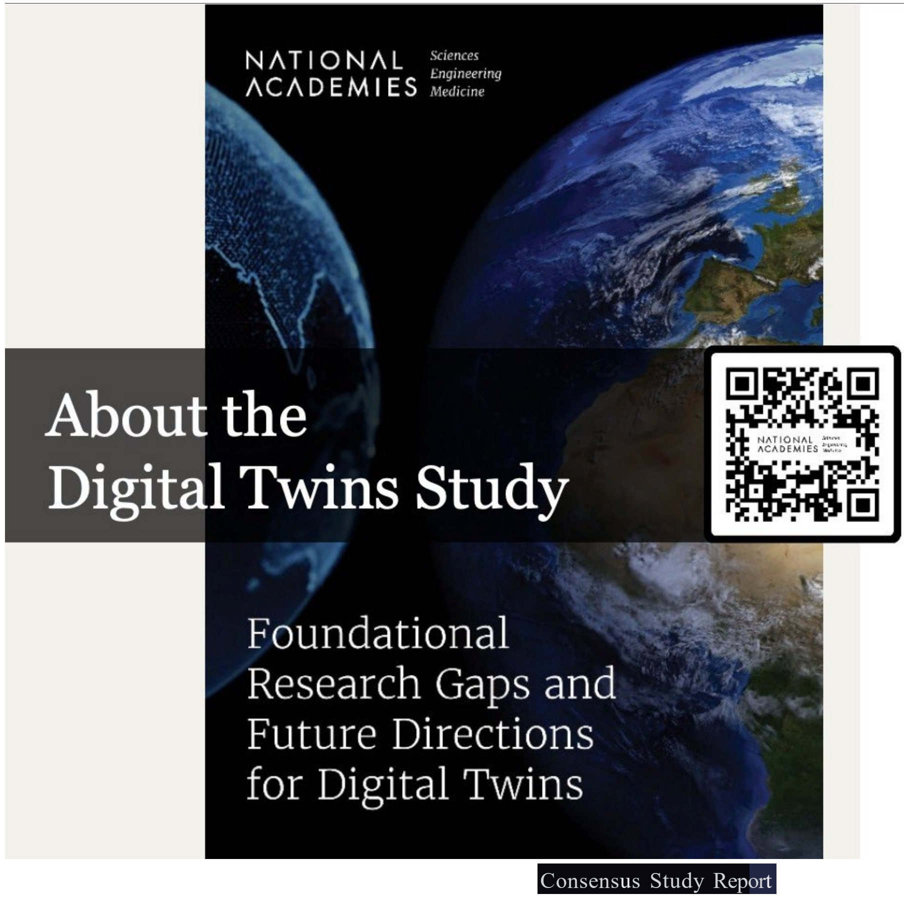
Mathematical, Statistical, and Computational Challenges and Opportunities for Digital Twins in the Built Environment

Omar Ghattas
Pratt Chair in Engineering
Professor, Department of Mechanical Engineering
OPTIMUS Center Director
Oden Institute for Computational Engineering & Sciences

Digital Twins in the Built Environment
National Academies of Sciences, Engineering, and Medicine
June 13, 2024

ODEN INSTITUTE FOR COMPUTATIONAL ENGINEERING & SCIENCES

THE UNIVERSITY OF TEXAS AT AUSTIN



NATIONAL ACADEMIES
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Medicine

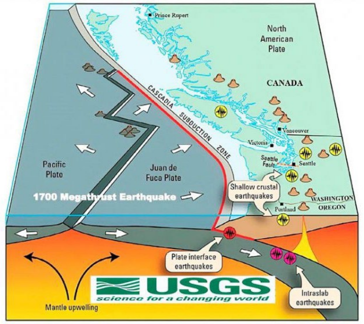
About the
Digital Twins Study

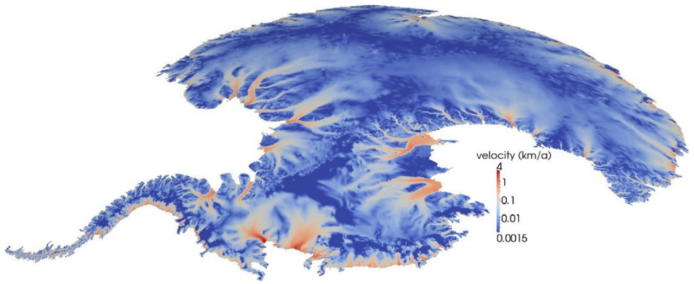
Foundational
Research Gaps and
Future Directions
for Digital Twins

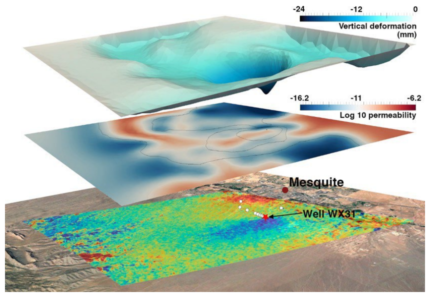
Consensus Study Report

Advancing mathematical, statistical, and computational foundations

- How are digital twins defined across different communities?
- Foundational research needs and systemic gaps
- Promising practices across domains and sectors
- Opportunities for translation of best practices across domains
- Use cases for awareness and building confidence
- Key opportunities in research, development, and application







Data assimilation

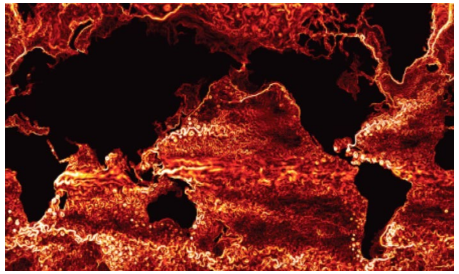
Physical system

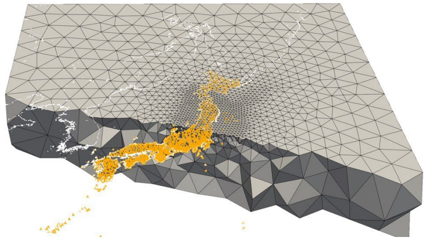
Mathematical Challenges for Predictive Digital Twins in the Built Environment

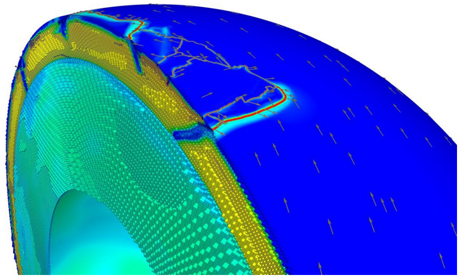
- Tight, dynamic interplay between data assimilation and optimal decisions
- Real-time operation
- High-consequence decisions demand UQ
- Real-time and UQ settings demand accurate and inexpensive surrogate models
- Potential for AI/ML surrogates to be game-changers

Digital Twin

Optimal decisions (control & exp design)







Thank you for joining us!

Slides will be posted on the event page in the coming week.

Please contact rdeboer@nas.edu with any questions or comments.

To learn more about the Digital Twins consensus study and sign up for emails about future events like this, head to the study webpage via the link or QR code here!

https://www.nationalacademies.org/digital-twins