arpa·e
CHANGING WHAT'S POSSIBLE

COOLERCHIPS™

MOSTCOOL

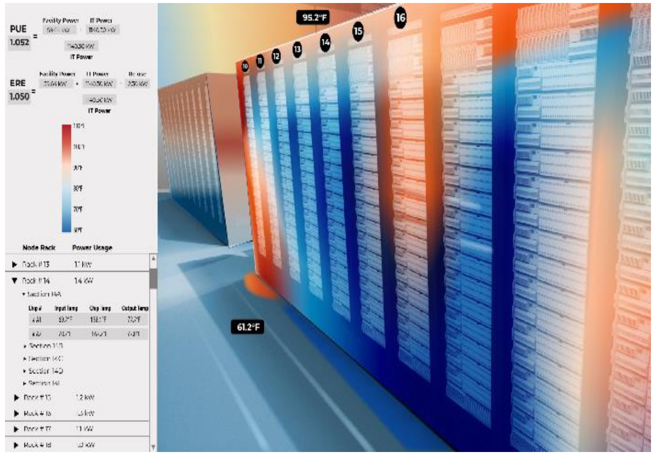
(Multi-Objective Simulation Tool for Cooling Optimization and Operational Longevity)

F.P. McCluskey, Univ. of Maryland, College Park

Team Members: NREL, LBNL, Univ. of Arkansas, Trane

Project Vision

- To develop an integrated co-simulation software toolset that can be used to optimize the design of data centers, including their data, power and thermal management systems for lower cooling energy demand, lower CO_2 footprint, and lower cost, while maintaining high reliability and availability
- To facilitate the adoption of this tool to achieve transformational and disruptive design advances, first by Track A and B performers and then by the larger data center design community.



Total Project Cost:	$3.91M
Length	36 mo.

COOLERCHIPS Kickoff Meeting
October 18 & 19, 2023

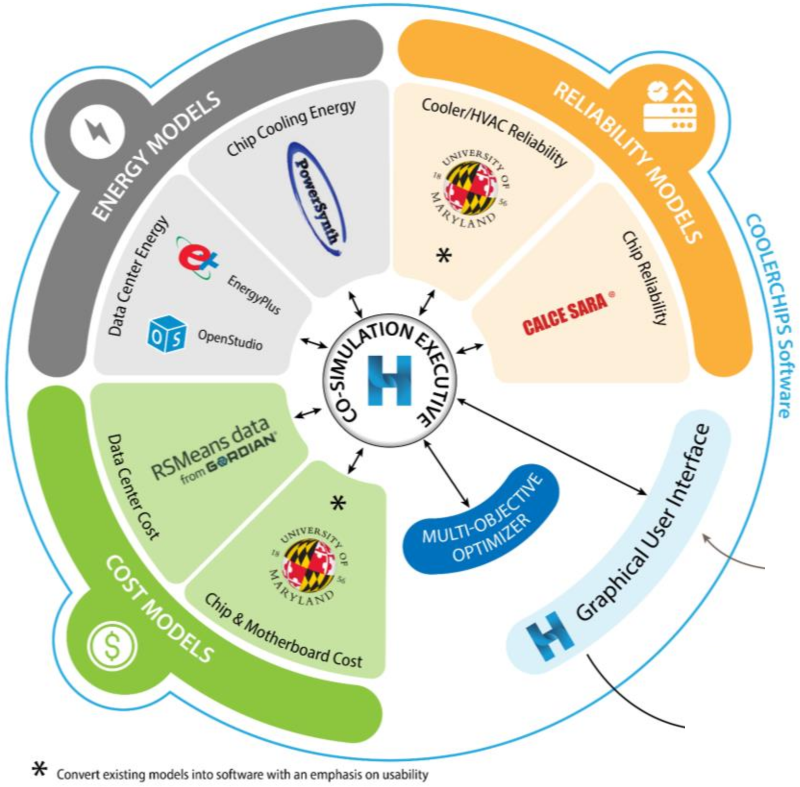
COOLERCHIPS Project Overview: MOSTCOOL

Fed. funding:	$3.48 M
Length	36 mo.

Team member	Location	Role in project, core competencies
University of Maryland	College Park. MD	***PRIME*** Thermal, Reliability, and Cost Analysis
National Renewable Energy Lab	Golden, CO	Software Integration/Development, Reliability
Lawrence Berkeley Nat'l Lab	Berkeley, CA	Building Scale Thermal, Energy, and CO2 Footprint Modeling
University of Arkansas	Fayetteville, AR	Module and Device Reliability
Trane	Davidson, NC	Building Models, Software Validation, Market Analysis

Integrate and enhance existing simulation models into a multi-objective co-simulation tool that when adopted will achieve transformational and disruptive data center designs that dramatically reduce data center cost, energy use, and CO_2 footprint while maintaining high reliability/availability.

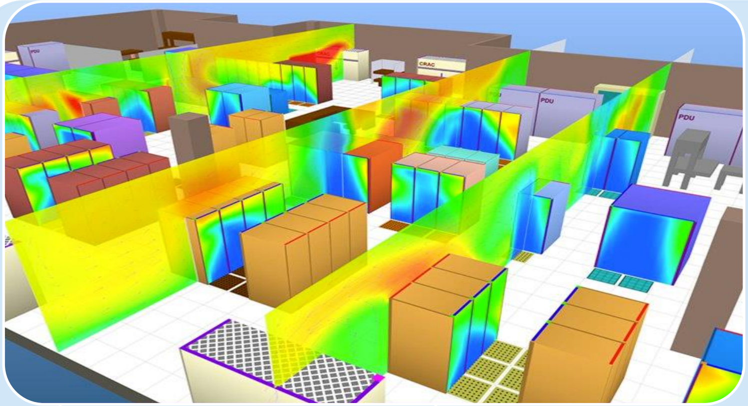
Program Metric	State of the Art	Proposed
Co-simulation	Individual simulations	Multi-objective optimization with user defined value functions
Interaction Model	No interactions	Second-order interactions
Tool use by data center industry	Use of individual proprietary tools	Open source tool for data center industry wide use



arpa·e
CHANGING WHAT'S POSSIBLE

Software Tool Capability Overview

Open source software providing seamless multi-physics simulation of data center scale thermal profiles, energy usage, CO_2 footprint, reliability, availability, and cost through a user-friendly GUI.



- Will include a base library of common cooling components
- Will allow modeled data center to be placed in any climate zone
- Will allow user to specify average/hourly climate conditions
- Common system model used for energy, reliability and cost analysis
- Users build custom component modules to interface with system model
- Estimates operational CO_2 emissions using national average or local carbon emission factors
- **Multiple releases with an aggressive time scale for improvement**

Thermal Modeling

- **Calculate rack and module temperature to within +/- 5°C**
- High fidelity modeling tools used to capture complex physics in the novel single-/two-phase cold plates developed by Topic A & B teams
- Reduced order modeling tools to model server & rack level cooling.

Availability Modeling

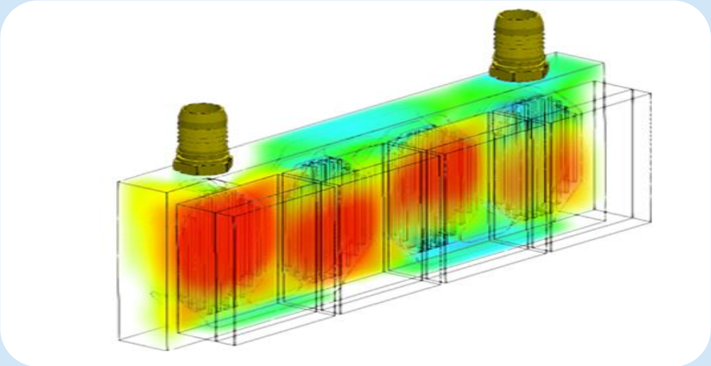
- **Predict availability to within < 1%**
- Availability determined using reliability block diagrams, Markov chain analysis, and Fault Tree Analysis.
- Based on PoF models for degradation of electronic and cooling systems requiring test data inputs from performers.
- FMEA score for component interactions

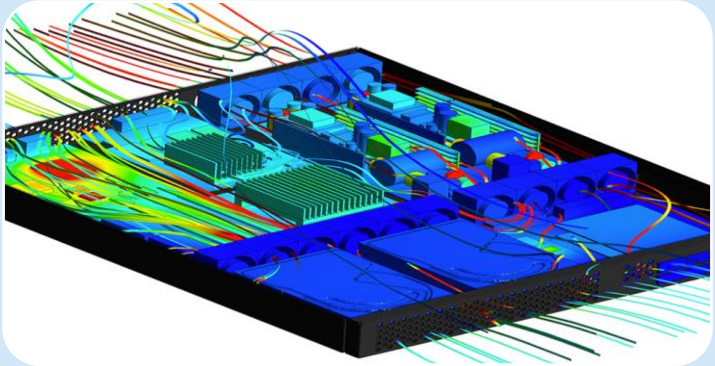
Cost Modeling

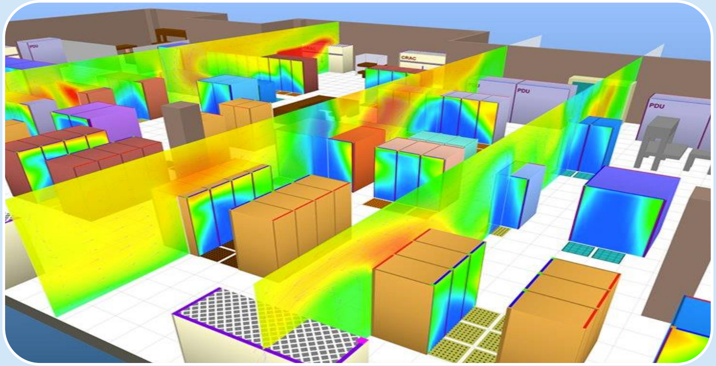
- **Path to calculate IRR and number of years to payback.**
- Will require data on cost per part, operational energy cost projection, inflation assumptions.
- Estimate both CAPEX and OPEX and allow tradeoffs such as costs of lower performance vs. costs of replacement/repair.

Thermal Modeling

The thermal profiles will be able to calculate the temperature of the racks and modules to within +/- 5°C







Level 1: Device Modeling

- Develop high fidelity modeling tools to capture complex physics in the novel single-/two-phase cold plates developed by teams in Technical categories A & B.
- Initial version release includes OpenFOAM based CFD solver with GUI interface followed by a PINN - PDE solver.
- Release demos for OpenFOAM solver and PINN solver for users.
- Create a data pipeline for data flow to higher level 2 and level 3 modeling.

Level 2: Server/Rack modeling

- Develop reduced order modeling tools to model server & rack level cooling.
- Make use of empirical relations and existing data to model air cooling on other components in a server and rack.
- Make use of data from the high-fidelity simulations in level 1 to mimic the novel heatsink to run the reduced order modeling.

Level 3: Data center modeling

- Make use of data from server/rack level as input conditions to data center model (e.g. pressure drop across server and power generation).
- Simplification of racks and servers based on level 3 modeling to reduce the modeling complexity and ensure faster and accurate modeling.

EnergyPlus – Building Energy/CO2 Modeling

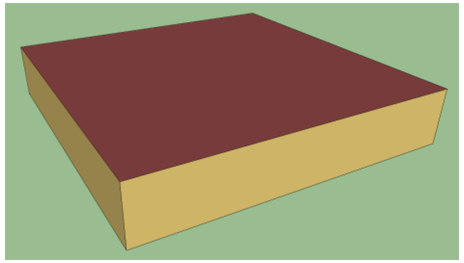
The energy usage profiles will be able to calculate energy usage to within <2% of IT load

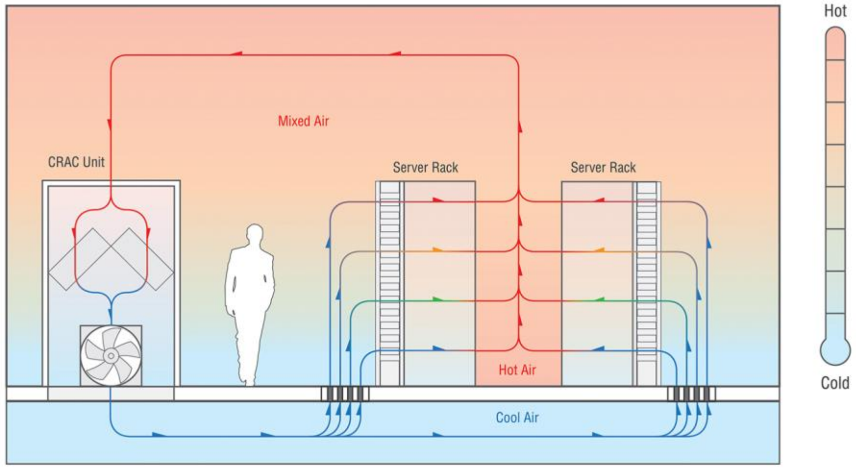
Inputs

- Building Characteristics: Envelope, HVAC, lighting, DC load
- Operation/use: HVAC schedule, setpoint, occupant schedules
- Utility rates
- GHG emission factors
- Weather data

EnergyPlus model

Field	Units	Obj1
Name		Data Center Servers
Zone or Space Name		Main Zone
Air Flow Calculation Method		FlowControlWithApp
Design Power Input Calculation Method		Watts/Unit
Watts per Unit	W	500
Number of Units		100
Watts per Zone Floor Area	W/m2	
Design Power Input Schedule Name		Data Center Operati
CPU Loading Schedule Name		Data Center CPU Lo
CPU Power Input Function of Loading and Air Tempera		Data Center Servers
Design Fan Power Input Fraction		0.4
Design Fan Air Flow Rate per Power Input	m3/s-W	0.0001
Air Flow Function of Loading and Air Temperature Curve		Data Center Servers
Fan Power Input Function of Flow Curve Name		ECM FanPower fFlo
Design Ente		
Environmen		
Air Inlet Con		
Air Inlet Roo		
Air Outlet Ro		
Supply Air N		
Design Rec		
Recirculatio		
Design Elec		
Electric Pow		
Fraction of E		
CPU End-U		
Fan End-Us		
Electric Pow		
Supply Tem		
Supply Tem		
Return Tem		
Return Tem		





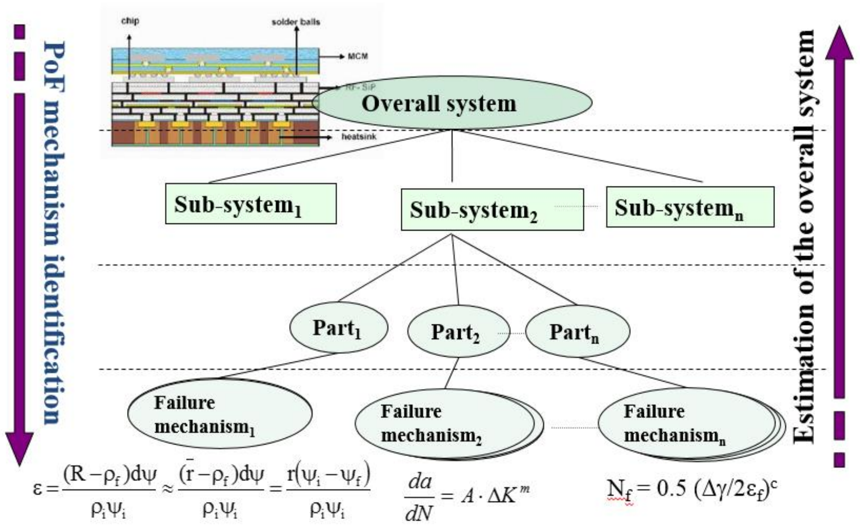
Outputs

- Energy: chillers, fans, pumps, lighting, DC, waste heat recovery
- Peak demand
- Operational CO2/GHG
- Utility costs
- Indoor environmental conditions: temperature, humidity

Energy – Accounts for pumping power of the liquid through the cooling system plus room air conditioning
CO2 Footprint – Based on energy source and likely linear with energy. Expressed in kg CO2/kWh

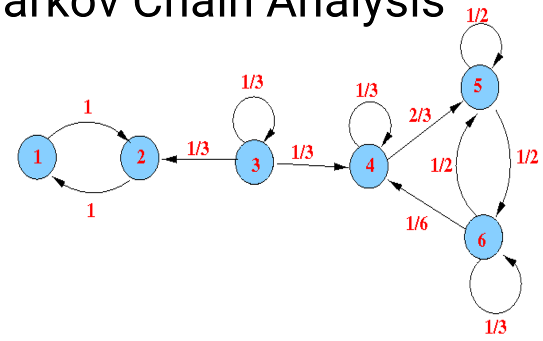
PoF Reliability Modeling

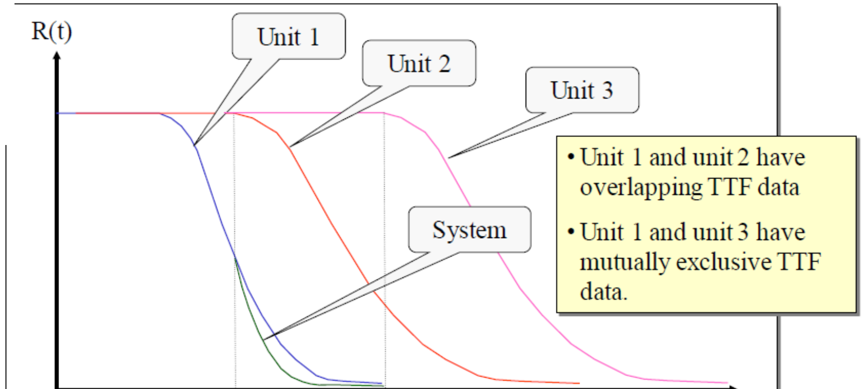
- Identifying and modeling dominant device and cooling system failure mechanisms
- Estimating time to failure for each element failing by each failure mechanism
- Using fault tree analysis/Markov chains for component inter-dependencies
- Using probabilistic mathematical approaches to combine independent distributions for identical or non-identical parts failing due to identical or non-identical mechanisms



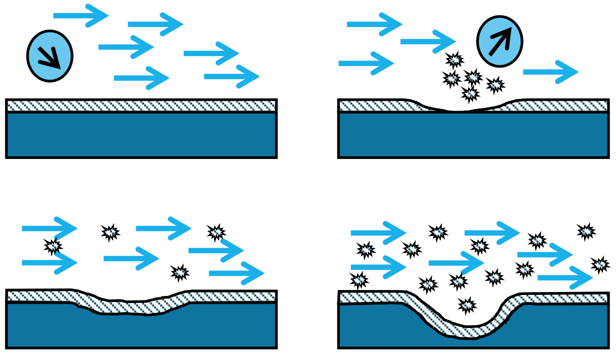
Failure Mechanism Modeling

Markov Chain Analysis

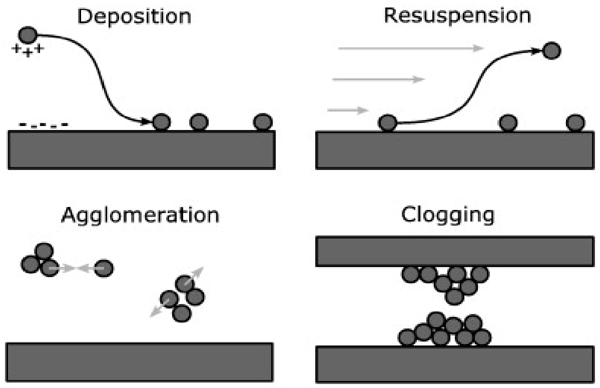




System Reliability



Erosion/Corrosion



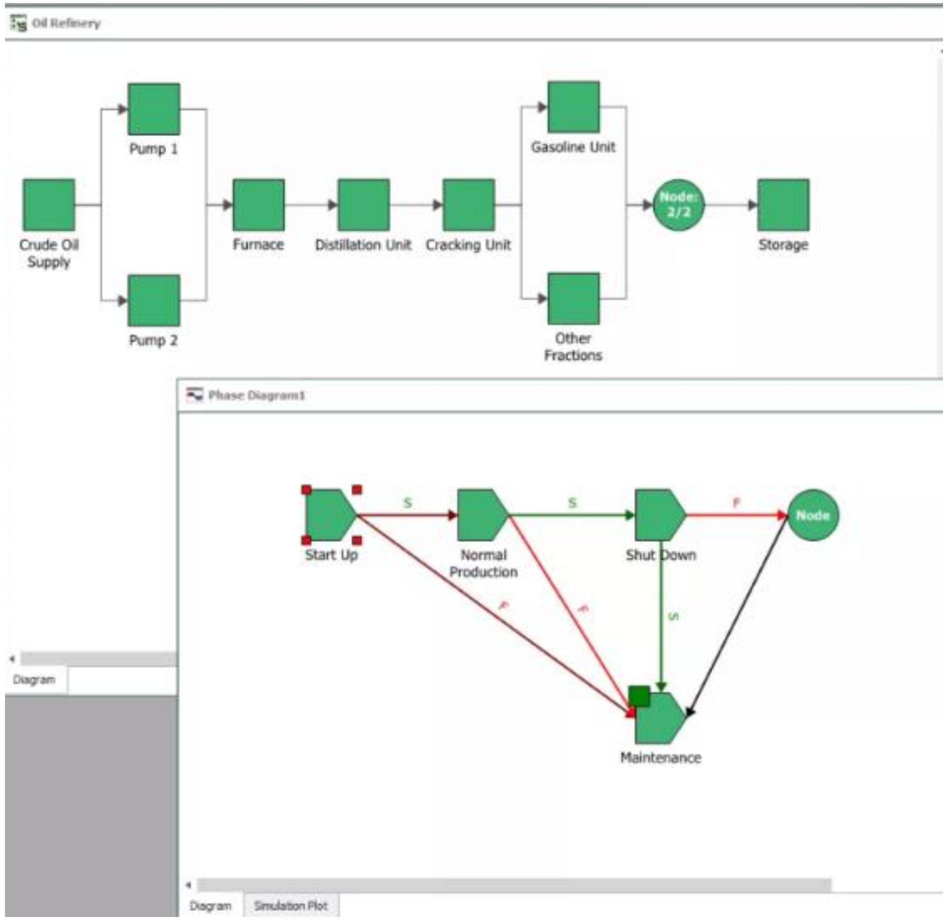
Fouling/Clogging

arpa·e
CHANGING WHAT'S POSSIBLE

Availability Modeling

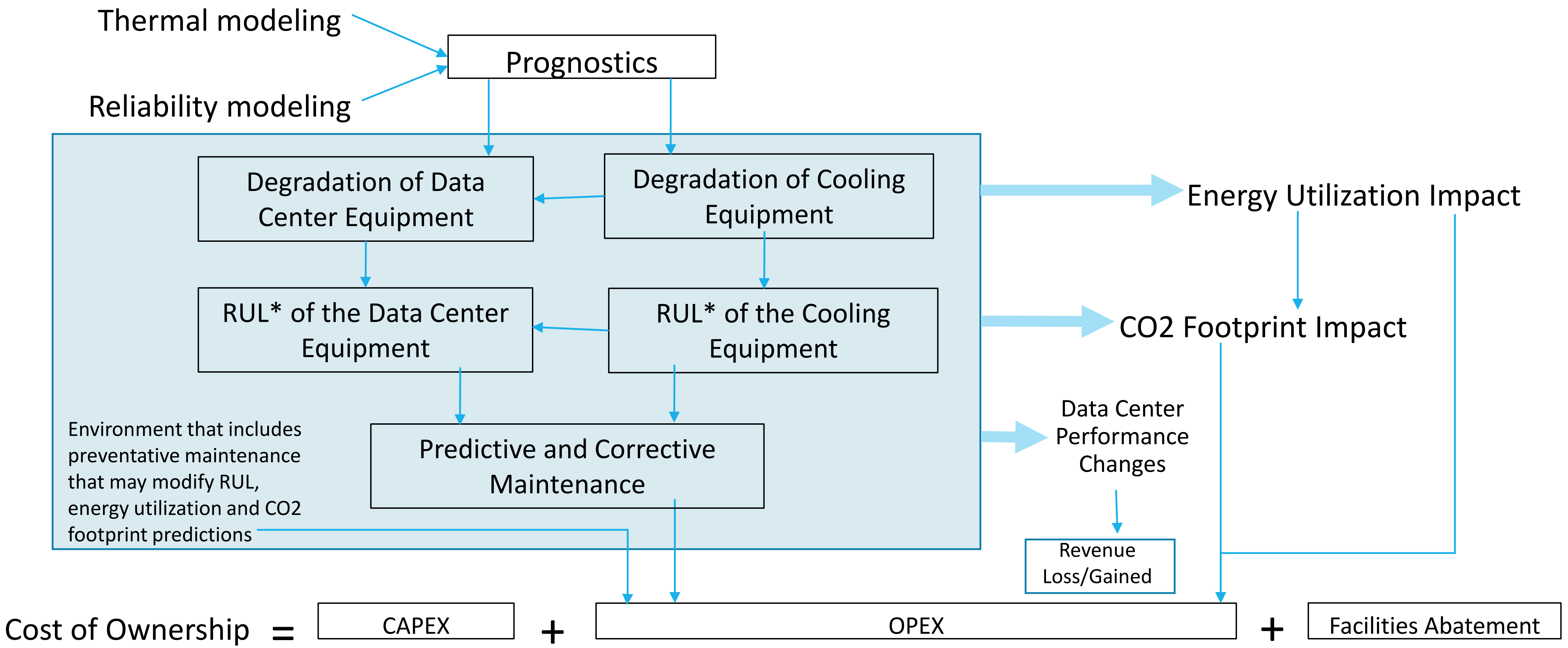
The availability software will be able to predict availability to within < 1%

- Construct a fault tree diagram of all components and possible failure modes to determine what combinations cause system downtime.
- Create a series/parallel reliability block diagram (RBD) of the system
- For each component, conduct a Monte Carlo analysis to determine a distribution of failure times based on the mechanisms causing earliest failures.
- For each RBD, run a series of Monte Carlo simulations, inserting a random failure time for each component within that component's failure distribution.
- Combine the failure times for each RBD, accounting for redundant components, where multiple systems would have to fail/require maintenance simultaneously for the system to go down.
- For each Monte Carlo iteration of an RBD that lasted one year without failure, there would be no downtime. For each iteration that failed, the length of downtime would be calculated.
- From the sum of all the downtimes for all the runs for all the RBDs, a system availability of total uptime/total time) would be generated.



Cost Modeling

Determine the total cost of ownership of the data center including its power and thermal management systems, and perform maintenance planning tradeoffs based on the forecasted RULs of critical equipment.



*RUL = Remaining Unit Life

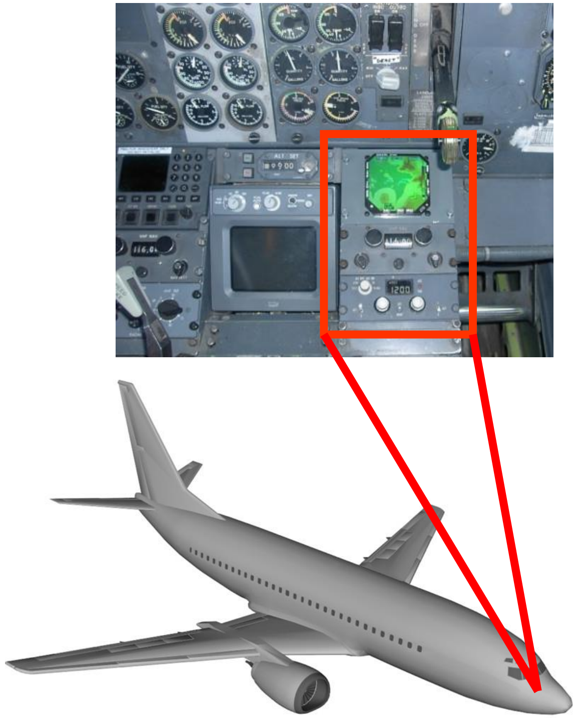
CHANGING WHAT'S POSSIBLE

Cost Modeling – System Life-Cycle Cost Outcome Example

Example system payback associated with predictive system health/maintenance management

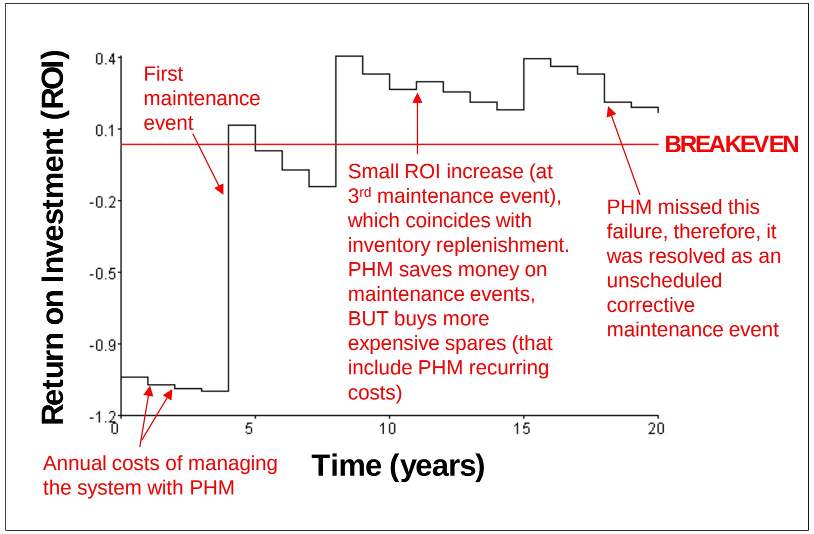
- Stochastic return on investment (ROI) analysis associated with the implementation of prognostics and health management (PHM) in an electronic display unit in a fleet of aircraft

Sandel ST3400 TAWS/RMI Electronic Display Unit

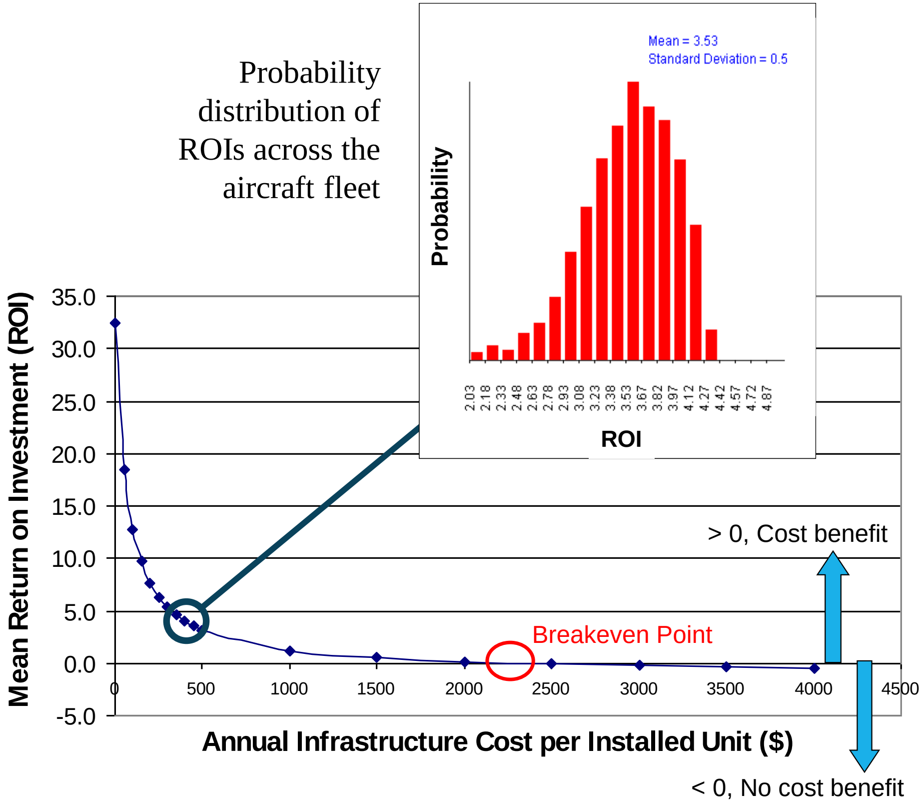


Example ROI (relative to unscheduled corrective maintenance) of one instance of the unit managed with PHM over its 20 year installation life

There are 502 aircraft in the fleet, each one has a unique maintenance history, this is the ROI experienced by one aircraft in the fleet



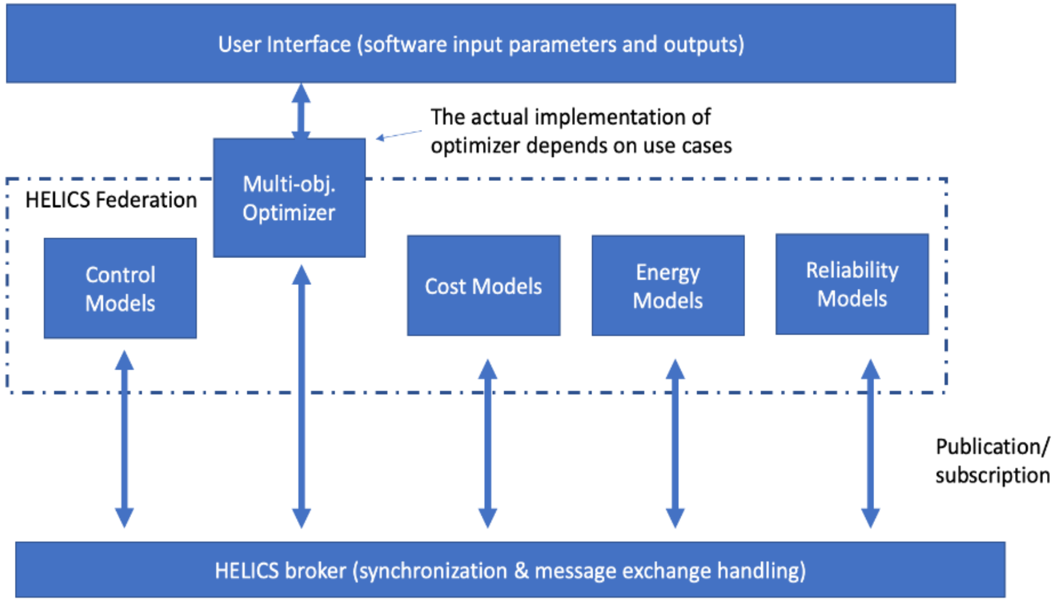
ROI (relative to unscheduled corrective maintenance) at the end of 20 years for 502 instances of the unit



arpa·e
CHANGING WHAT'S POSSIBLE

Co-Simulation Platform Selection

- Co-Simulation Platform actively coordinates shared simulation time with robust data exchange and supports multi-rate (time step) systems.
- Landscaped five co-simulation platforms. Performed detailed, multi-platform assessment of openBuildNet, HELICS and Mosaik.
- HELICS selected as co-simulation platform (core)
  - Multi-platform (Windows, Linux, HPC Linux-based clusters)
  - Supports physics and controller model development environments using many common tools (C, C++, Python, Modelica, Matlab, Julia)
  - Established contacts for collaboration with DOE National Labs for HELICS improvements



Criteria	*openBuildNet*	*HELICS*	*Mosaik*
Simulation setup	• Through any supported programing language. • Simple and less overhead. • Inline configuration. • Uniform interface for all supported tools/languages.	• Through any supported programming language. • Moderately simple and less overhead. • Separate and inline configurations. • Uniform interface for all supported tools/languages.	• Only through Python. • Moderately complex and with some overhead. • Inline configuration. • Interface varies with programming language / tool.
Synchroniz'n	• Global Clock	• Parallel and iterative	• Time, event and hybrid
Arbitration	• Explicit ordering	• Implicit and parallel	• Explicit ordering
Data throughput and reliability	• Connection setup delays. • Intermittent packet loss.	• Reliable connection setup and data transfer. • ZMQ Support • MPI Support • Message filters available to shape network traffic	• Reliable when using inbuilt network sockets. • ZMQ extension does not support handshaking. • No MPI Support
Simulation management	• Multi-rate support. • Distributed nodes. • Node drop identification.	• Multi-rate support. • Distributed nodes. • Node drop handling.	• Multi-rate support. • Distributed nodes. • Node drop handling (only with inbuilt protocol).
Additional framework utilities	None	• Single point simulation control. • Data collection tool. • Data generation tool.	• Single point simulation control. • Data collection tool.

Task Outline & Technical Objectives

- The software will provide seamless multi-physics simulation of data center scale thermal profiles, energy usage, CO2 footprint, reliability, availability, and cost.
  - Thermal profiles calculate the temperature of the racks and modules to within +/- 5°C.
  - The energy usage profiles calculate energy usage to within <2% of IT load
  - The availability software will be able to predict availability to within < 1%
- Multi-objective optimization with value functions set by user.
- Second order interactions, such as between thermal and reliability, between availability and cost, and between energy usage and CO2 footprint
- **FIVE RELEASES**

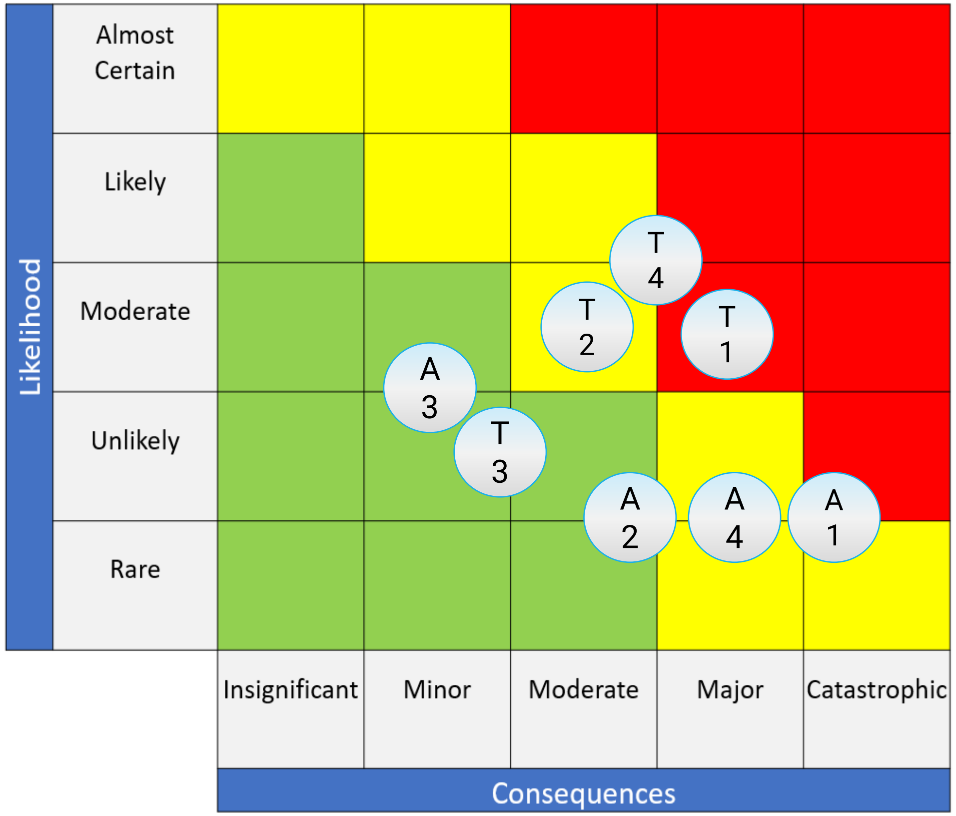
Quarter	Release	Contains	Timing
2	1.0	Thermal, Energy, Cost, CO2 Footprint Models	Initial Release
4	2.0	Reliability, Availability Models	Before Q6 Rack Demo
7	3.0	Building Scale Models	Before Q9 Full Demo
10	4.0	Beta Release	For Public Review
12	5.0	Final Release	End of Program

WBS	Task/Milestone Title	Task/Milestone Description	due Q
M1.1	**Go/No-Go:Refine tasks & milestones (if applicable)**	**Go-No/Go Milestone: Refine tasks and milestones for the work plan (if applicable)**	**1**
M1.2	Modeling Needs Identified	Document modeling needs for the common cooling approaches for Team A and B teams. Outline the structure of the toolset.	1
M1.3	Market Survey	Document relevant SOTA software modeling packages tools and capabilities. License review.	1
M1.4	Energy Model Validation	Show that the Energy software can model the NREL/LBNL typical data rack or other reference to within 10%.	2
M1.5	Initial Cost Analysis	Baseline cost scenario for typical data rack or other reference.	2
M1.6	**Release 1.0:** Energy/Thermal Model Release	**RELEASE 1.0:** Release of the Energy and Thermal Modeling Software Elements	2
M1.7	Software Model Integration	Integration and Interoperability of Two or More Modeling Elements Achieved	3
M1.8	Cooler Reliability	Physics of Failure Models Developed for Cooling Component Reliability	3
M1.9	Guidelines	Provide Testing and Design Guidelines	3
M1.10	**Release 2.0:** Initial Integrated Tool Release	**RELEASE 2.0:** Initial Release of the Integrated Tool Containing Thermal, Energy, Reliability, Availability, and Cost Tools.	4
M1.11	Building Scale Model	Models Extended to Address Building Scale Assessments	5
M1.12	Marketing Plan	Initial Commercialization and Adoption Plan Developed	5
M1.13	Graphical User Interface	Initial User Interfaces Modified Based on Performer Feedback and GUI Enhanced for Integrated Software Toolset at Building Scale	6
M1.14	**Go/No-Go: Adoption**	**User Adoption and Successful Modeling by a Plurality of A and B Teams**	**6**
M2.1	**Release 3.0:** Final Release for Teams A&B	**RELEASE 3.0:** Release for Full Design Review of Performance Targets (includes Integrated Software with Updated Models for Thermal, Energy, Reliability, Availability, and Cost).	7
M2.2	Optimization and Interaction	Flexible optimization value function definition software developed. Inclusion of second order interactions between model elements.	8
M2.3	GUI for External Release	Full GUI and Documentation developed for Release to External Data Center Community	9
M2.4	**Release 4.0:** Beta Release to Public	**RELEASE 4.0:** Beta Release to Public and Hosting of Workshops for Software Adoption/Feedback by Data Center Community	10
M2.5	Post-program Commercialization	Post-program plan for commercializing the software tool developed.	10
M2.6	Final Software Revisions	Complete data operations optimization and paralleling.	11
M2.7	**Release 5.0:** Final Public Release	**RELEASE 5.0:** Final Public Release	12

CHANGING WHAT'S POSSIBLE

Challenges and Risks

Risk Status



Risk	Technical Risks	Explanation/Mitigation
T1	Insufficient or inadequate input information for the modeling.	• Reliability needs validated model constants, materials of construction, design dimensions, and life cycle loads. (guideline for tests and getting info) • CO_2 needs database of Mt per process • Thermal and energy need power dissipations and cooling parameters (COP, heat flux) • Availability needs redundancy and reliability input • Cost needs availability, repair, and replacement cost
T2	Interoperability of the disparate modeling software packages.	All programs need to get input from a common user interface and output that is accessible by HELICS.
T3	Inappropriate Basis or Weighting Factors for Optimization	Optimization function is available to the performers to set the optimization criteria, Cost, CO2 Footprint, Availability.
T4	Models not sufficiently accurate with required run time or flexible for disparate cooling solutions	Many different scenarios for cooling. Work with Track A and B performers to convert their complex FEA/CFD models to high fidelity surrogate models for thermal, reliability, etc.

Risk	Adoption Risks	Explanation/MItigation
A1	Not available when needed by performers	Initial integration of currently available software with rapid improvement cycles and a carefully timed release schedule.
A2	Lack of knowledge of performers' modeling and analysis preferences	Biweekly/Monthly Communication with Topic A and B performers starting with the one-on-one meetings today.
A3	Difficult to use (poor interface)	Several releases to accommodate feedback on user effectiveness from the Topic A and B performers
A4	Commercial options chosen instead	Extensive benchmarking of existing software and its limitations to showcase how this software is superior

CHANGING WHAT'S POSSIBLE

Communication Plan:

Three-level Organizational Structure

Inner circle – Meets Online Biweekly

- Core project team
- Representatives from Track A and B performers

Second level – Meets Online Monthly

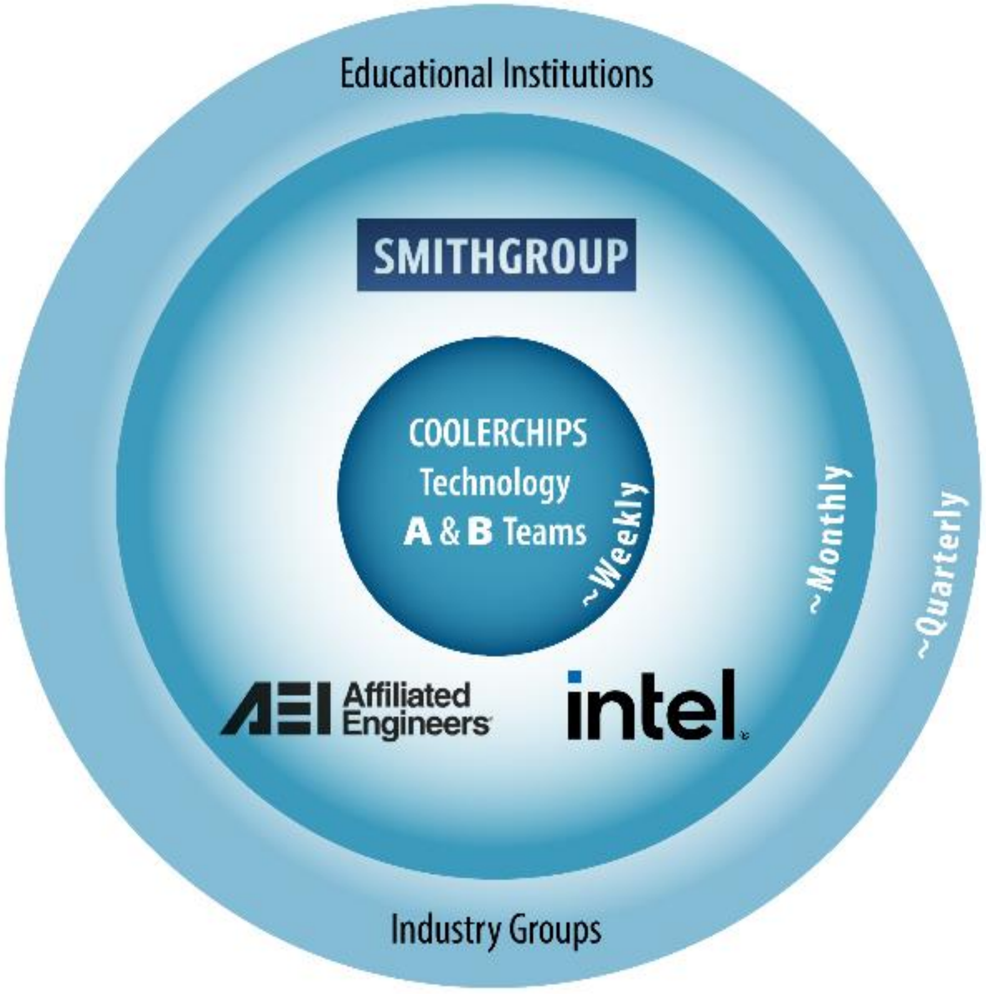
- Corporations from the data center industry that have shown interest (i.e. Intel, AEI, and SmithGroup) in our work,

Third level – Meets Online Quarterly

- Advisory board consisting of a diverse group of educational institutions, corporations, and industry professional groups in the wider data center community

Semi-annual in-person meetings

- Entire three-level membership and DOE representatives.
- Coincide with software releases.



arpa·e
CHANGING WHAT'S POSSIBLE

Technology-to-Market Approach

- This proposal team includes the lead developers of OpenStudio and EnergyPlus.
  - Proven track record of success bringing open source software technologies to market.
  - Among DOE's most downloaded software programs
  - Will borrow approaches and proven channels used for OpenStudio and EnergyPlus, including GitHub
- NREL has an outstanding command of industry best practices for software development
  - CI/CD and integrated, comprehensive software testing.
  - Automated extended-validation code signing workflow to ensure cyber-security and quality requirements.
  - OpenStudio and EnergyPlus software incorporated by companies like Trane, Carrier, and Autodesk
- NREL has strong credentials in partnering with many universities,
  - OpenStudio and EnergyPlus are intertwined into multiple curricula.
  - Network of partnerships with university programs dedicated to enhancing buildings, including data centers.
  - Existing channels can be leveraged for introducing COOLERCHIPS software
- The proposal team includes Trane employees who are responsible for developing Trane's industry-leading TRACE software for designing and building heating, ventilation, and air conditioning (HVAC) systems.
  - Trane's has track record of leveraging open-source software for commercial products and offerings
  - Trane will also bring its business acumen and market experience to advise the larger proposal team to ensure the COOLERCHIPS software is best positioned to meet the industry's data center design needs.
- With Intel representing computer chip manufacturers and SmithGroup and AEI representing the data center design and construction industry, the proposal team will receive insightful advice on ensuring COOLERCHIPS software has features and functionalities most needed by corresponding industry sectors.
- OpenStudio and/or EnergyPlus are included in many building design and construction workflows, COOLERCHIPS software will be more easily incorporated into these workflows, maximizing its impact.

We are looking forward to our one-on-one discussions with each team this afternoon.

Please bring your answers and thoughts regarding the questionnaire provided before this workshop.

Q & A

https://arpa-e.energy.gov