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Human Factors, Human-Machine Teaming, and the Cognitive Science of Real-Time Operations

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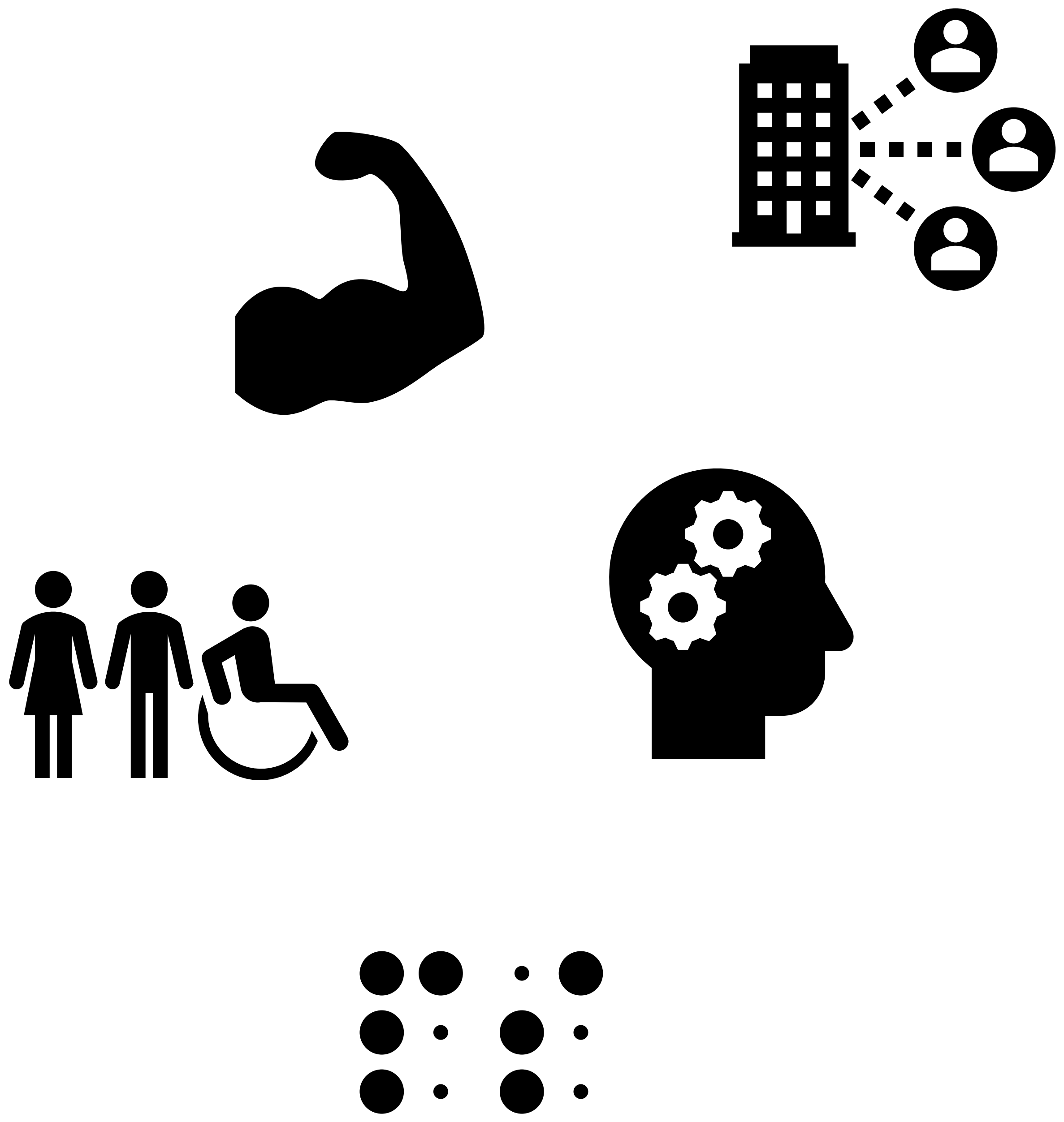
“Human error is often cited as the main cause for up to 80% of all incidents and accidents in complex, high-risk systems…”

https://www.nerc.com/pa/rrm/hp/Pages/default.aspx

What is Human Factors?

Human Factors is the systematic measurement of human behavior, ability, and limitations in an application to system design, tasks, environments, and equipment.



Purpose

Integrating new technology requires more than a great idea:

- Are there human limitations that will impact the technology?
- Do users possess the necessary expertise to use the technology?
- Will the technology demand too much of the user's attention?
- Will users reject the technology for other reasons (policy, politics, personal beliefs)?

For successful technology deployment we must consider the end user, and how the technology will be integrated into the existing work environment and how it will be used. But more importantly, how will the tool or technology adequately address the end user's needs, and how do we know what those needs are?

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Some Great Examples of Human-Machine Teaming

Framing the Domain

- Human Factors (Ergonomics) examples
  - Human Performance
  - Human-Machine Interface
  - Human-Machine Teaming
  - User Experience
- Physical location for Operations
  - Offices
  - Control Rooms
  - In the field

- Primary discussion will be around **deployment of technology and human-machine teaming for real-time operations in a control room environment**.
- Many of these concepts also apply in other grid applications
  - Training
  - Cybersecurity
  - Maintenance and Operations (M&O)
  - More
- The stuff we're not talking about today
  - Worker Safety and Heath
  - Safety Metrics, Injury Rates
  - Continuous improvement strategies, near misses, and close calls, Lessons Learned

Introducing Technology into the Real-time Operating Environment

Primary Role of Electric Grid Control Room Operators

Mission: Reliable and safe operations

- Keep the power on
- Make sure nobody gets hurt or killed when the power is on
- Protect assets

- Staffed by small teams, 3-5 dispatchers per shift
- Shifts are typically 12-hour rotating between days and nights, with overlap at turnover

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Example Questions for Human Factors

- **How is numeric information displayed?** – 5K vs. 5,000 vs. a bar chart
- **How often is information updating?** – too fast for an engineer to notice vs. too slow to be useful
- **How much information is presented?** – 10 sources each communicating something very different vs five very similar types of data that could be confused, and other display related questions
- **Is the operator's trust in the tool well calibrated?** – Over-trusting leads to failure to catch system errors, under-trust may result in unwarranted rejection of the tool.
- **How many hours are operators/ engineers spending on a task?** – Humans fatigue during long work periods and even during short work periods (90 minutes) depending on cognitive load. Imagine pressing a red button every 2 minutes or so for 90 minutes. You'll make mistakes guaranteed. It's not because the task is hard. It's because you're fatiguing.
- **How many tasks are operators/ engineers tending to?** – Task complexity and number of tasks have been shown to influence error rates in a number of domains. Classic human risk assessment literature has looked at nuclear systems engineers and shown that for multi-step procedures, the number of steps impact the number of errors resulting when that procedure is carried out.
- In teams, **is there mutual understanding of the task to be completed?** – Having common ground in teams can facilitate self-organization and aid in communication between team members. When there is a lack of common ground, safety and security can be put at jeopardy.

Human Factors:
Tying it all Together

Human Factors Methodologies

Methodologies

- **Controlled Experimentation** – The systematic manipulation of variables to measure their effect on other variables. These studies usually include a control condition that serves as baseline and an experimental condition to test one's hypothesis.
- **Field Observation** - Passive viewing and/ or measurement of a phenomena or occurrence. Typically includes note-taking, video/ audio recordings, and collecting measurements.
- **Knowledge Elicitation/ Extraction** – The process of gathering the known processes, facts, and general understanding of a system from a person. Most commonly, this is performed with a person with expertise in a particular field, or of a process. Methods can include:
  - Cognitive Task Analysis
  - Heuristic Evaluation
- **Modeling** - A quantitative or qualitative description of a process or phenomena. Cognitive modeling is a model that describes process mechanisms, neural mechanisms, or general components of human decision making with respect to some task. Mental models are often convenient diagrams to depict decision processes.

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Each method has advantages and limitations depending on the goals of the research

Table 1 The strengths and weaknesses of each method according to various evaluation criteria

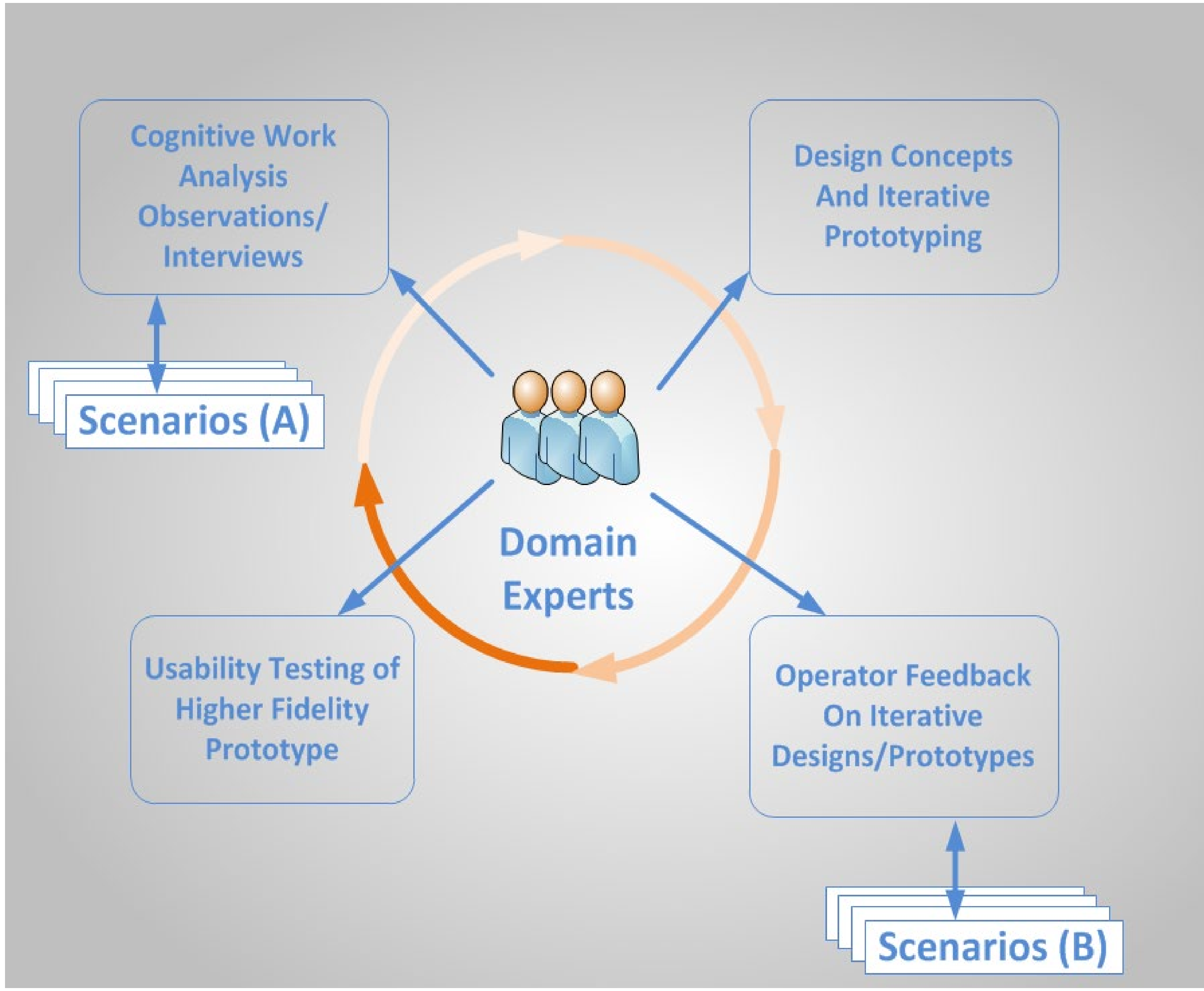
Method Strengths	Controlled Experimentation	Field Observation	Cognitive Modeling	Cognitive Task Analysis	Heuristic Evaluation
Can Compare performance across conditions	Green	Yellow	Green	Yellow	Yellow
Can investigate causal relationships	Green	Red	Green	Red	Red
Allows for quantitative evaluation	Green	Green	Green	Yellow	Yellow
Efficient/Cost effective	Yellow	Yellow	Green	Yellow	Green
Insights from domain experts	Yellow	Green	Yellow	Green	Yellow
Investigate cognition that drives behavior	Green	Yellow	Green	Green	Yellow
Findings generalize to the operational environment	Yellow	Green	Yellow	Green	Yellow

Green – Method meets criteria
Yellow – Method is not ideal for meeting criteria but is possible
Red – Method does not meet criteria

32

Design using Cognitive Task Analysis (CTA) Methods

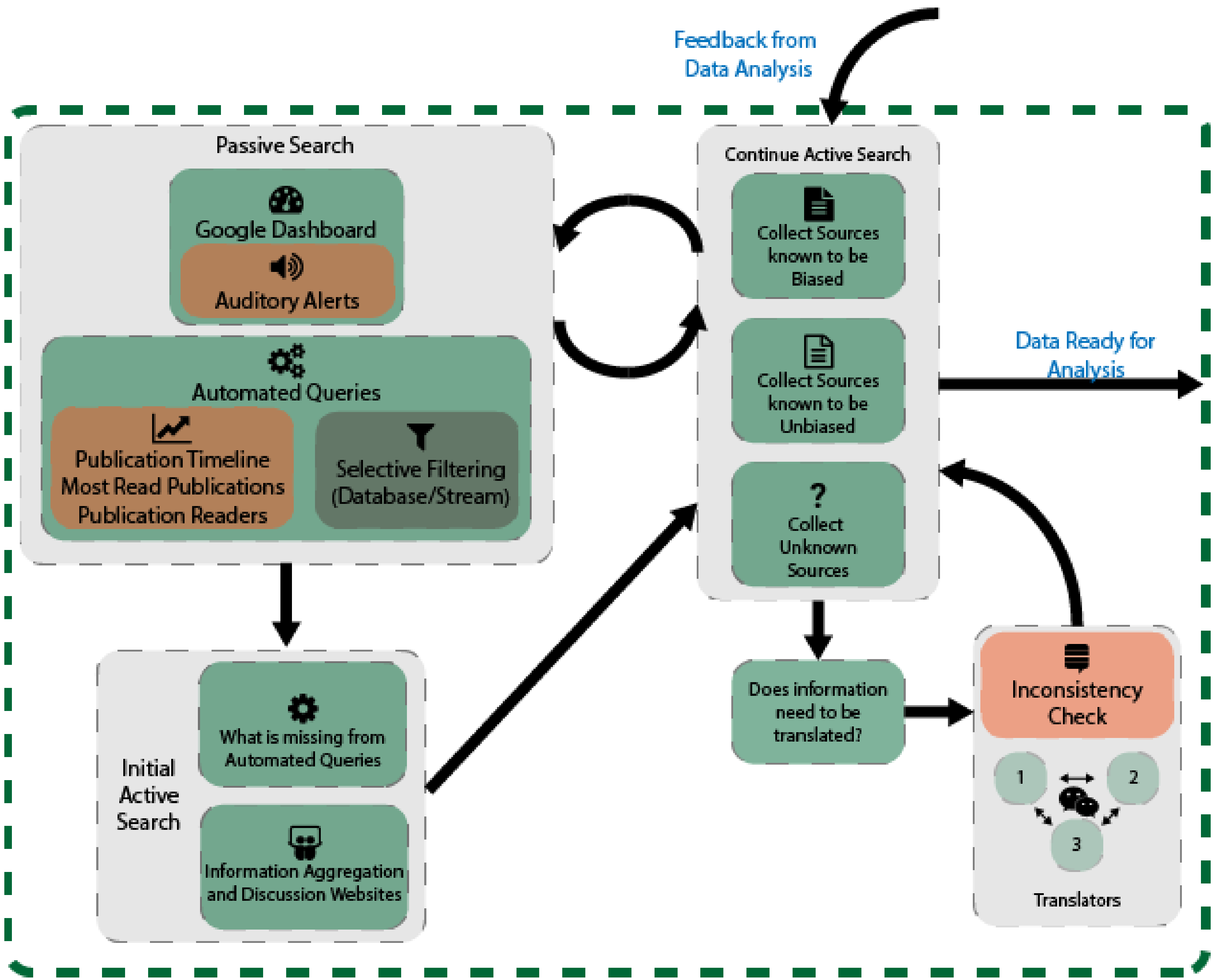
- End users are the domain experts.
- Create a set of functional requirements based on perceived needs of users and refine them.
- Prepare initial set of use case scenarios and present them to the users.
- Conduct cognitive work analysis through observations/interviews.
- Develop a wide spectrum of design concepts based on the user's needs and gather feedback.
- Revisit the design through iterative prototyping.
- Create a second set of use case scenarios to further explore the designs.
- Generate high-fidelity compositions of the visualizations.
- Test visualizations with operators in a control room environment with real or simulated data.



Risk Assessment Methodology

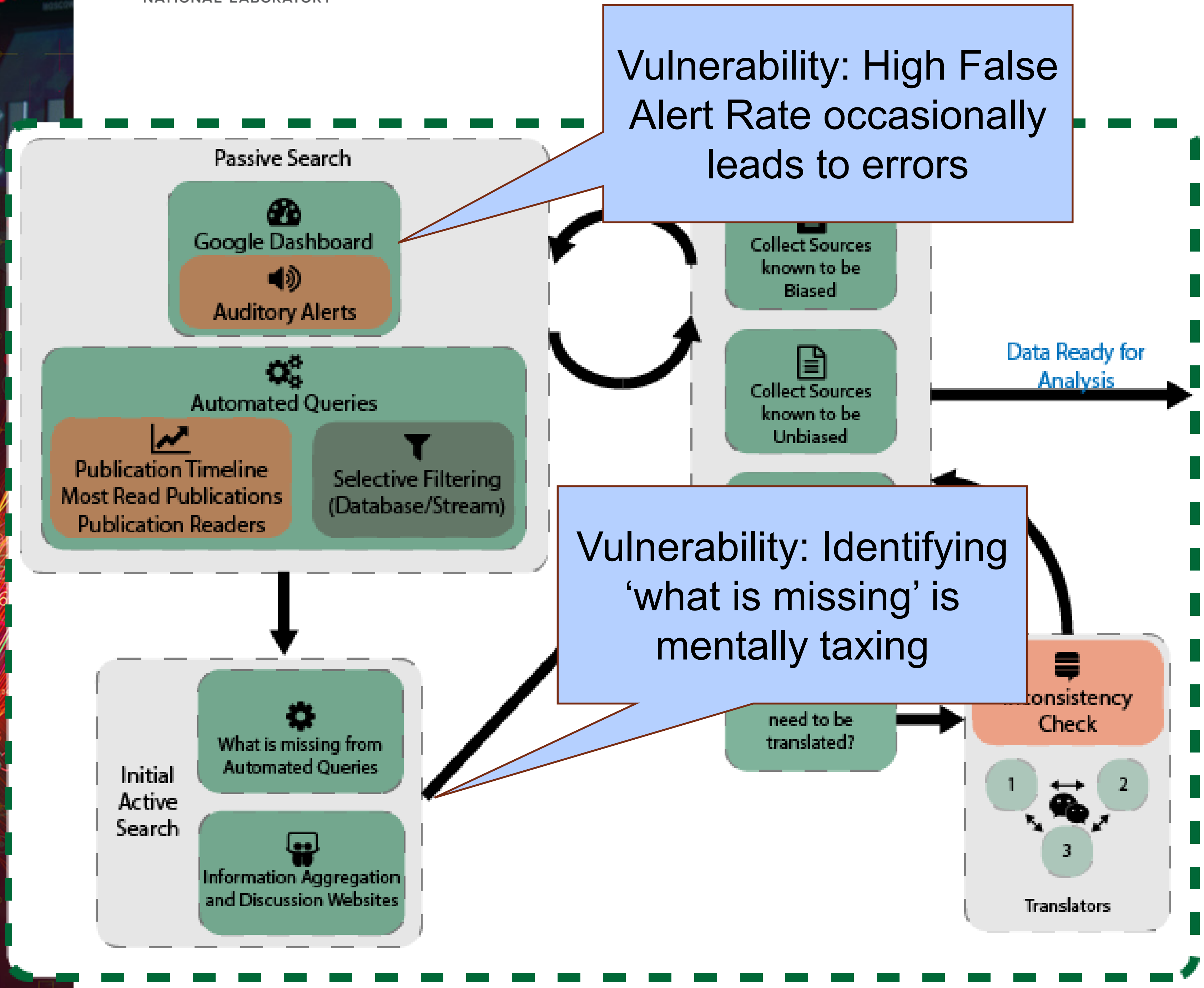
1. Gain deep understanding of the existing workflow through surveys, interviews and observations
2. Identify current threats and vulnerabilities in the workflow and quantify risk
   - Example Threat – Misdiagnose a fault
   - Example Vulnerability – Operator Fatigue
3. Identify opportunities where technology might benefit to reduce risk
4. Assess prototype technology’s ability to reduce risk
   - Mitigate existing vulnerabilities
   - Do not introduce new vulnerabilities

Gain Deep Understanding of the Existing Workflow



Data Collection

Identify Current Threats and Vulnerabilities and Quantify Risk



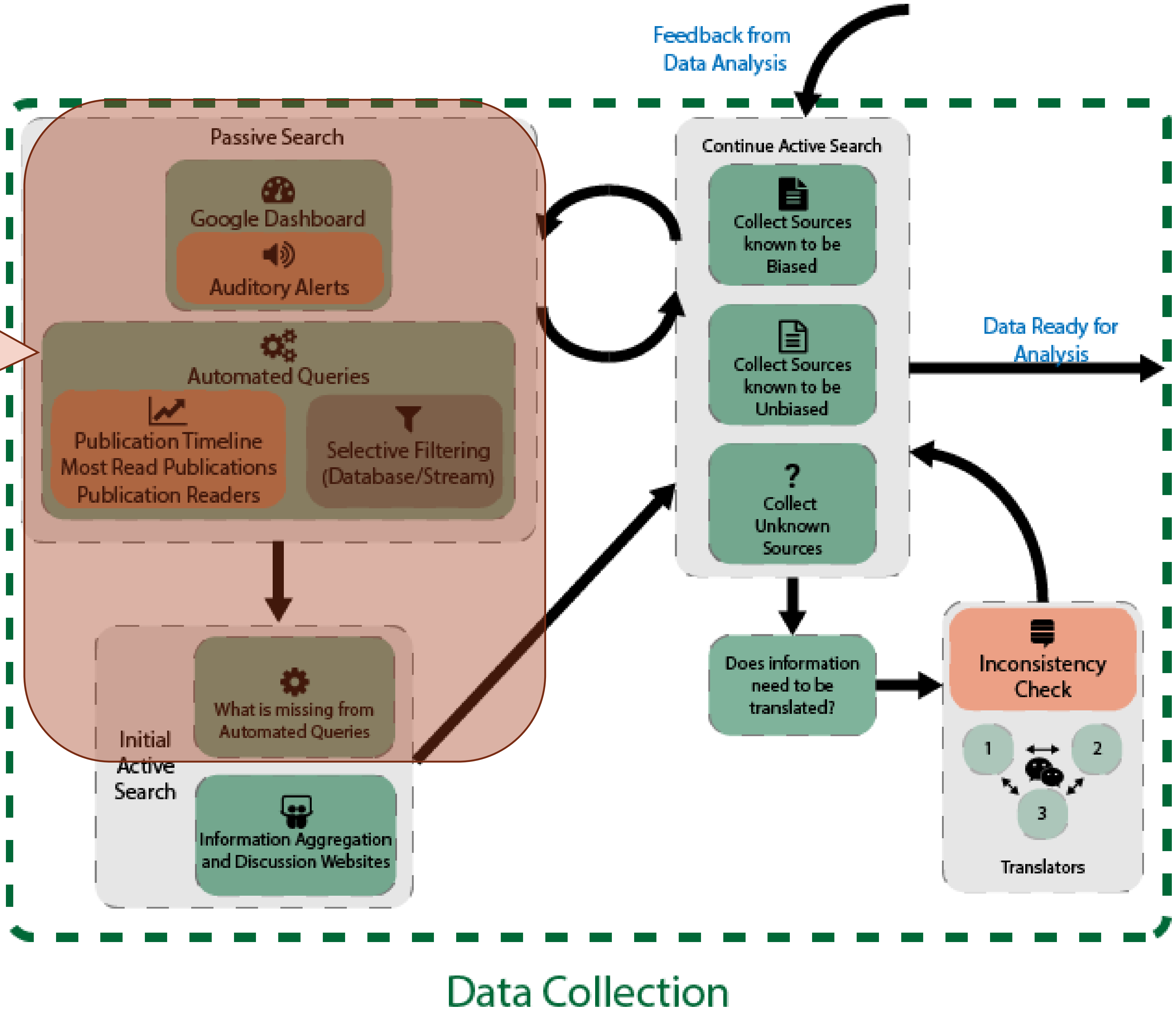
Once identified, components of risk (including vulnerabilities) can be quantified via operator ratings and/or performance measures.

Risk components can be combined to compute an overall risk score.

Identify Possible Technology Solution

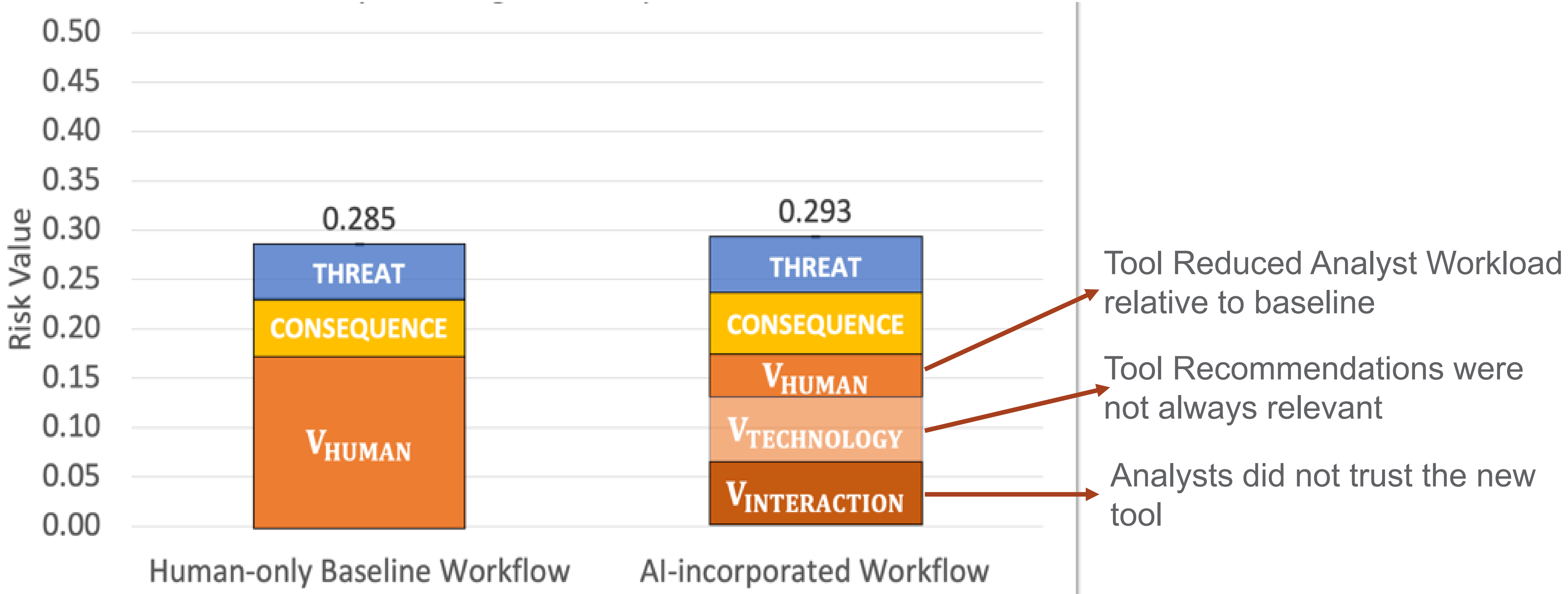
Advanced AI includes. . .

- Smart Alerting System
- Data Filtering Recommendations
- Recommends Content for Active Search



Assess Technology's Ability to Reduce Risk

The new tool did not reduce risk because risk reduction was offset by the addition of new vulnerabilities

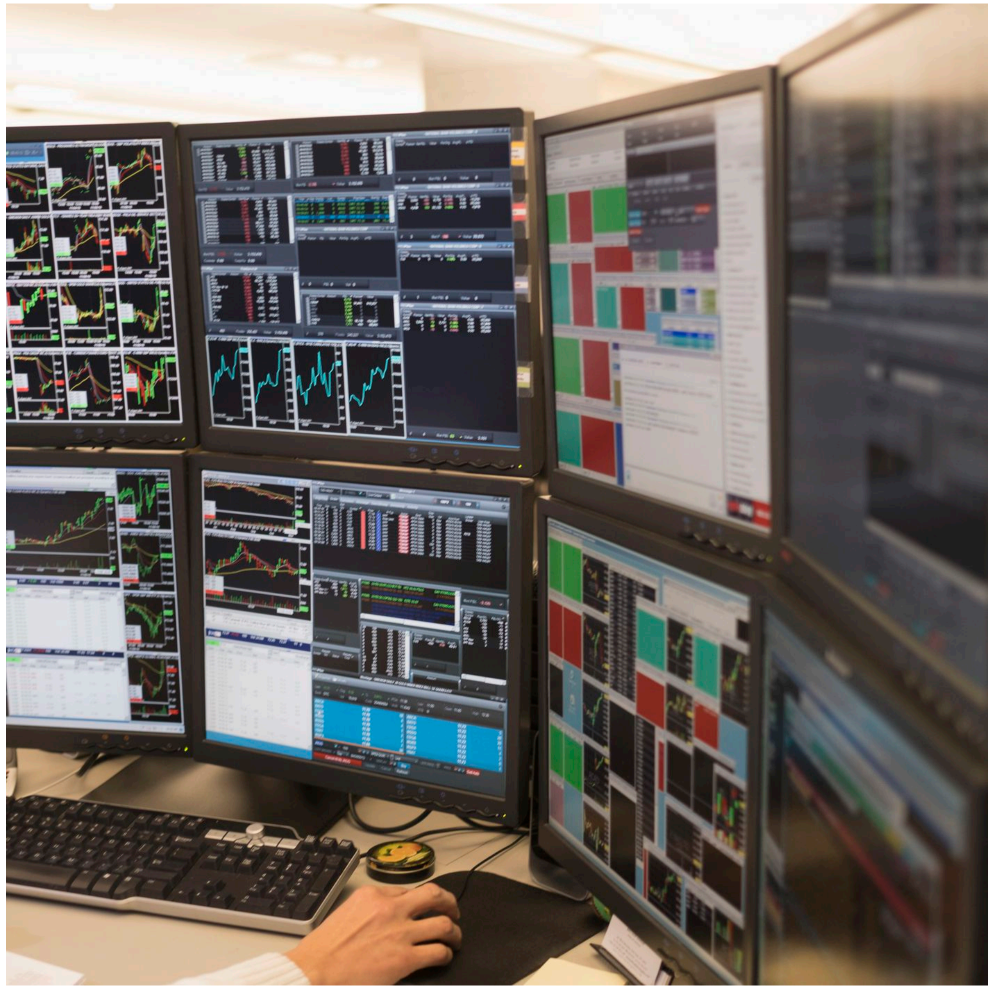


Note. Graph contains notional data for the purpose of illustration

Benefit or Detriment?

Adding one more display or tool to an existing workflow may cause more harm than good.

- Tool may not be used due to lack of trust in the technology
- Display may increase operator workload by presenting operators more data
- Learning curve may be too high to justify tool use



Power Grid Considerations – a Matter of Trust

Challenges to technology deployment

- False Alarms - notification that an event has occurred in the absence of the actual event

- Nuisance Alarms – while not technically false, they may also distract operators
  - Alarms that generate excessive audio and/or visual signals
  - Are generated unnecessarily
  - Do not turn off after corrective action is taken

- Cascading Alarms - occur when a series of interconnected events occur each setting off its own alarm.

Trust

- Over-trust – This usually leads to over-reliance on automation for decision making or for reliable data. Can lead to scenarios where human expertise would provide a more safe, effective, or desired outcome
- Under-trust – This leads to under-reliance on automation. Often humans are limited by cognitive load, reaction speed, and the ability to quickly reason a solution to a complex problem. By under-relying on the tools designed for effective (and sometimes safe and secure) decisions, users may cause more harm than good.
- Automation bias – Biases inherent in rule-based algorithms have to be measured and accounted for by users. Understanding the automation's biases (tendency to take a particular course of action, even when unwarranted), is the first step in increasing its trustworthiness.

Under-Trust

- What leads to under-trust?
  - Overly complex automation – automation surprise
  - No transparency
  - Automation Errors
- Potential Consequences
  - True alarms get ignored
  - Operator performs tasks manually (less efficient/safe)

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Over-Trust

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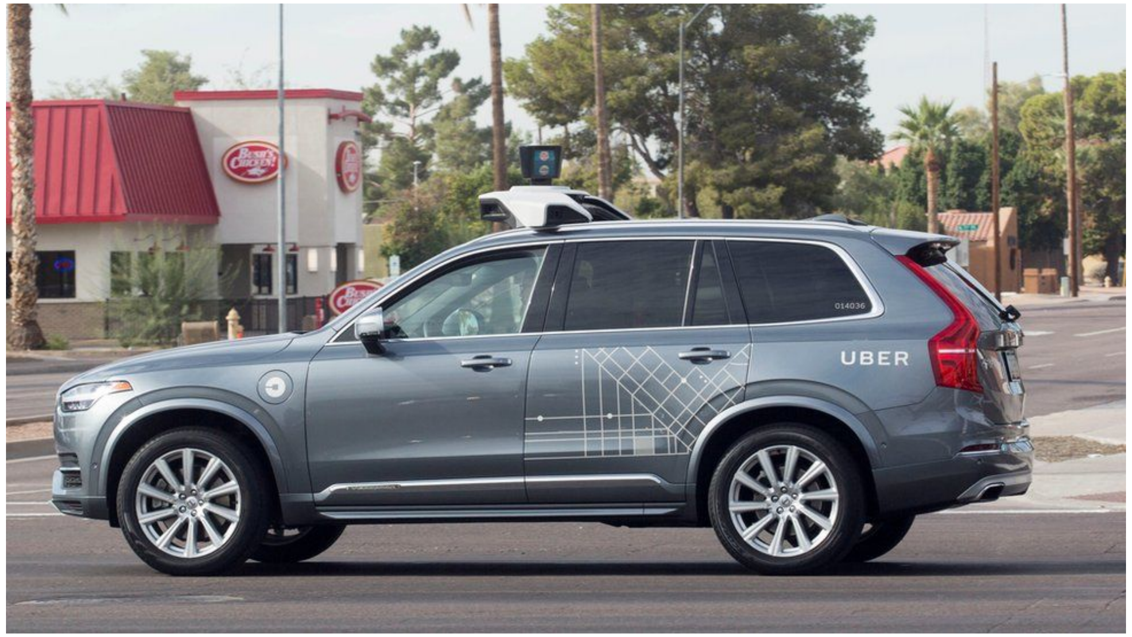
Over-Trust

- Complacency
  - Relying or complying with the automation even if it is inaccurate
  - Failure to monitor the automation to be sure it is working properly
  - Not a problem until automation fails
- 'Out of the loop unfamiliarity'
  - When failures do occur, they are difficult to detect
  - Operator has lost awareness of the situation and is less able to deal with the failure if it does occur
  - Operators' skills at performing the function begin to degrade

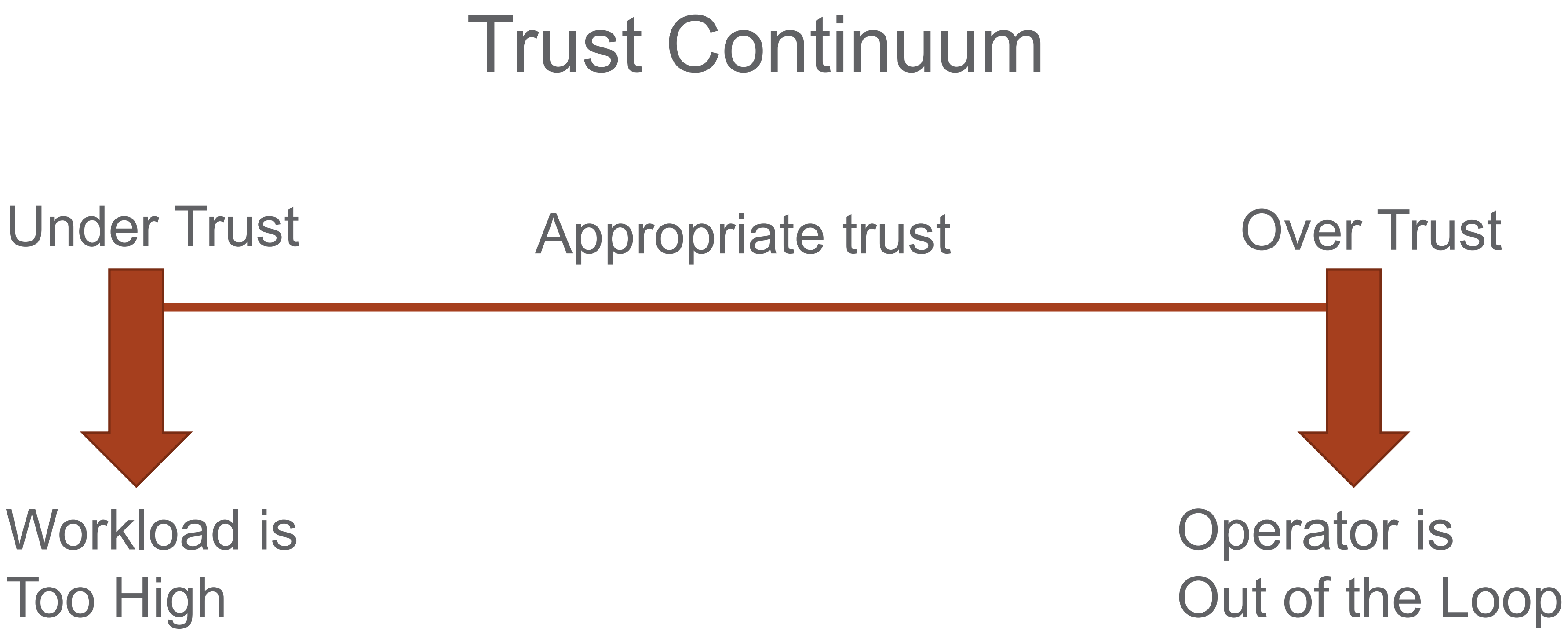
Humans and Machines Working Together: A word on Auto-Pilots



Uber's self-driving operator charged over fatal crash

https://www.bbc.com/news/technology-54175359#:~:text=The%20back%2Dup%20driver%20of,Tempe%2C%20Arizona%2C%20in%202018.

Finding Right Balance



Power Grid Considerations – Signal Detection

Indicator Characteristics

- When monitoring system status, operators rely on a variety of indicators to signal status changes.
- When these indicators (alarms, status updates, notifications, etc.) are weak or difficult to detect, it hinders the operator's ability to maintain situational awareness and perform the duties expected.
- It is important to understand how important indicators are designed and what those signals are supposed to communicate.

Sensor Characteristics

- Related to signal properties, the sensors out in the field or in the control room must be tuned to gather **relevant** and **enough** data to support operators.
- Sensors that are too sensitive may cause "information overload" and sensors that are too weak will miss critical data.

Decision Making

Many factors are important when considering decision making and decision makers.

- Time Pressure
- Complexity of the environment
- Impacts/ consequences of the decision
- Perceived real-time elements in the workplace
- Decision Support Tools
  - Trust in those tools
  - Trust in the data the tools rely on

Two Systems Involved in Decision Making

System 1 operations

- Produces intuitive decisions
- Automatic
- Involuntary
- Influenced by Affect

System 2 operations

- Produces analytical decisions
- Controlled
- Voluntary
- Effortful

Heuristics

- Mental Shortcuts
  - Can lead to poor judgments
  - Example - Availability Heuristic

Is it safe to fly?

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Decision Support

Events

E1

E2

•
•
•

En

Event Reasoning Tool

If and/or

EDS Impact

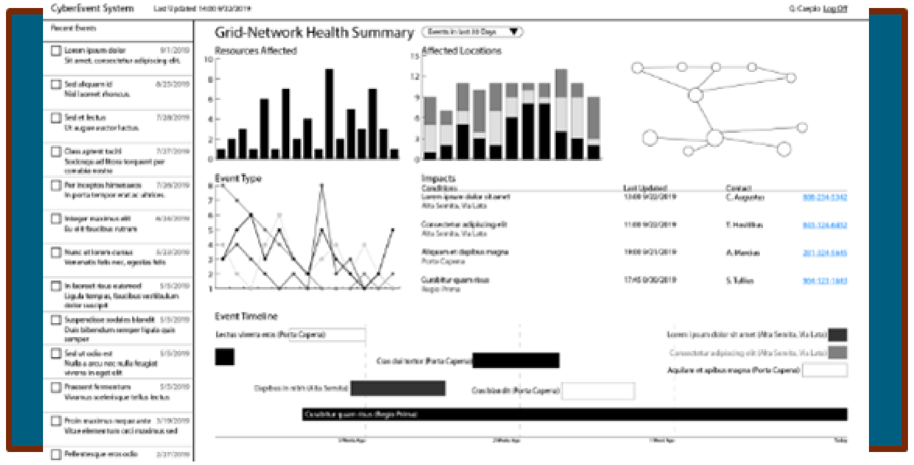
Notification

Control Room — EMS Alert

OT Cyber — RT Alert

Enterpise — Email/IM/txt

Human In the Loop



Cognitive Load

- ***Cognitive Load*** is the processing burden associated with a task or activity.
- In control rooms, operators are responsible for many simultaneous tasks (monitoring the system, responding to alarms, conducting reliability assessments, communicating with other control centers, writing switching orders, etc.)
- Cognitive load for incorporating new technology into the workflow may be high despite the technology promising to ease the burden.
- Cognitive Load can be decomposed into two parts. *(Sweller 2011)*
  - Intrinsic Load – The demands stemming from the intrinsic nature of the information to be managed. Perceiving and processing large numbers is harder than perceiving and recognizing colors.
  - Extraneous Load – The demands stemming from how information is presented and communicated. Audio presentation in noisy environments vs. visual presentation on a small monitor.

Situation Awareness

- Endsley's (1995) three levels of situation awareness
  - Level 1 - the ability to correctly perceive information in the environment.
  - Level 2 – comprehension - once correctly perceived, information must also be comprehended in the context of the current task and goals.
  - Level 3 - projection. This level involves taking level 1 and 2 knowledge as well as experience from past events to anticipate future events.

In addition to studying SA at the individual level, researchers have also studied SA across teams (Stanton et al. 2017). The concept Team SA includes two components.

- Each team member's SA for the individual elements of their work
- The degree to which all team members share the same SA for the shared operational requirements of their work

Fatigue

- Mental fatigue is the state of debilitated cognitive capability.
- Several causes for mental fatigue include:
  - Sleep deprivation
  - Extended time on a task
  - Difficulty of a task
- The effects of mental fatigue include:
  - Increased distractibility
  - Lowered discriminatory capacity
  - Negative impact on attention
  - Reduced efficacy of learning

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Human-Human, HMT Teaming

Human – Human Teaming
- Team Leadership
- Mutual Performance Modeling
- Backup Behavior
- Adaptability
- Team Orientation

Human – Machine Teaming
- Mutual Performance Modeling
- Adaptability
- Human Trust
  - Reliance
  - Appropriate Use

Also Coordinating Mechanisms
- Shared Mental Models
- Mutual Trust
- Closed-Loop Communication

TABLE 4. Applied metrics.

Human	Machine	Team
Adaptability	Usability	Cohesion
Assertiveness	Fan Out	Interventions
Impulsiveness	Robot Attention Demand	Intervention Response Time
Cohesiveness	Collision Count	Neglect Tolerance
Perseverance	Plan Execution	Unscheduled Operations Time
Extraversion	Plan Idle	Time Autonomous Operations
Conscientiousness	Plan out	Time in Manual Operations
Humility	Plan State	Plan State
Occupational Interest	Resource Depletion	Situation Coverage
Psychomotor processing	Interaction Effort	Task success
Stamina	Mutual Delay Time	Task Difficulty
General health	Neglect Tolerance	False Alarms
Fatigue	Settling Time	False Positive Interaction Rate
Stress	Time in Autonomous Operations	False Negative Interaction Rate
Situation Awareness	Time in Manual Operations	Interaction Efficiency
Attention Allocation Efficiency	Unscheduled Operations Time	Network Efficiency
		Recognition Accuracy
		Team Productivity
		True Negative Interaction Rate
		True Positive Interaction Rate

Research Metrics   Non-Research Metrics

"Machines do not have the same kinds of processing limitations as humans, so it is hard to imagine a situation in which a human would need to take over tasking from an MAA purely to lighten its workload, or in which an MAA would not perform a task for its user if it knows how to do it." ~ Haimson et al 2019

Social Aspects of Teaming

Use case: Cybersecurity

Operator fear

- Needing another tool would imply that they are not doing their jobs well
- Distraction from current tasks
- Automation taking away job

Personality conflicts – blue vs. white collar

Teaming issues - 24/7 shifts vs. day shift

- *Operator responsibilities* - Keep the power on, keep people safe, and protect assets
- *Cyber responsibilities* – IT perspective: Check the logs, fix the problems, and keep things running, compliance concerns
- *Language barriers* - Operator doesn't speak fluent cyber; Cyber may not know how to speak OT, and may not know what's in a substation

Conclusion:
Tool Development in a Cognitive-rich Environment

From design perspective:

- This is a great tool
- We're here to help
- This tool will help users to be more efficient at their job
- Automation is better than doing it manually

From user perspective:

- Every other tool I've seen doesn't work
- I don't need your help, and I didn't ask for it
- Your tool will make me less efficient
- You're trying to take our jobs away

End users opinions are jaded because:

- Too many tools have been rolled out without proper testing and verification and validation (V&V) to include the human in the loop.
- Too many tools result in additional workload because of false alarms.
- Too many tools don't get used because the operators can't trust them to work correctly.

And the #1 reason:

- Too many tools get developed without early engagement of the #1 stakeholder: ***the end users***.

Next Steps

- We are working on a report that looks at human factors-related issues. The report is being finalized and the location it will be posted is still being discussed with the sponsor. Wherever it lands, we can provide notification and a link to it on the NASPI website.

- We are also conducting an operator survey on the control room real-time operating environment. The survey is ready to launch, and we’re looking for utility partners that can make operators available for about an hour to complete the survey.

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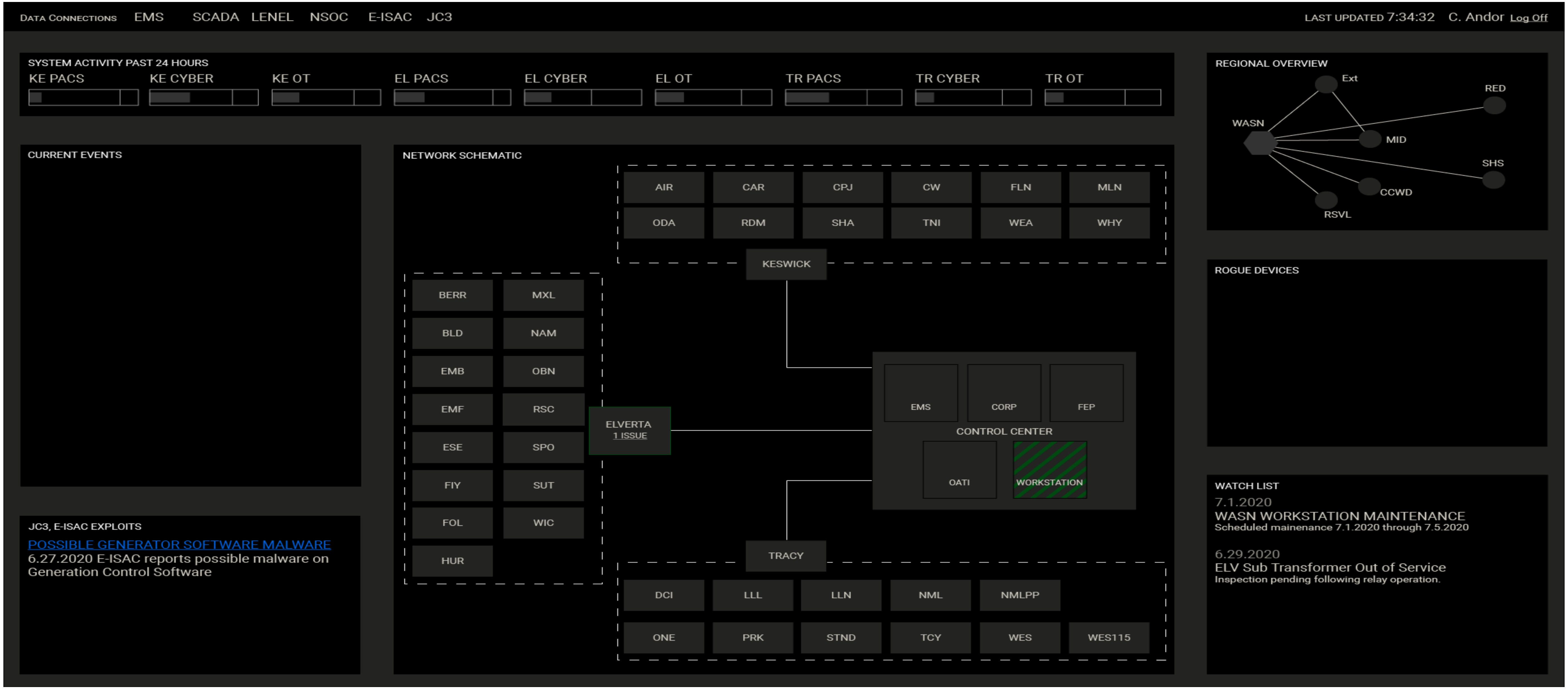
OT Cyber Dashboard



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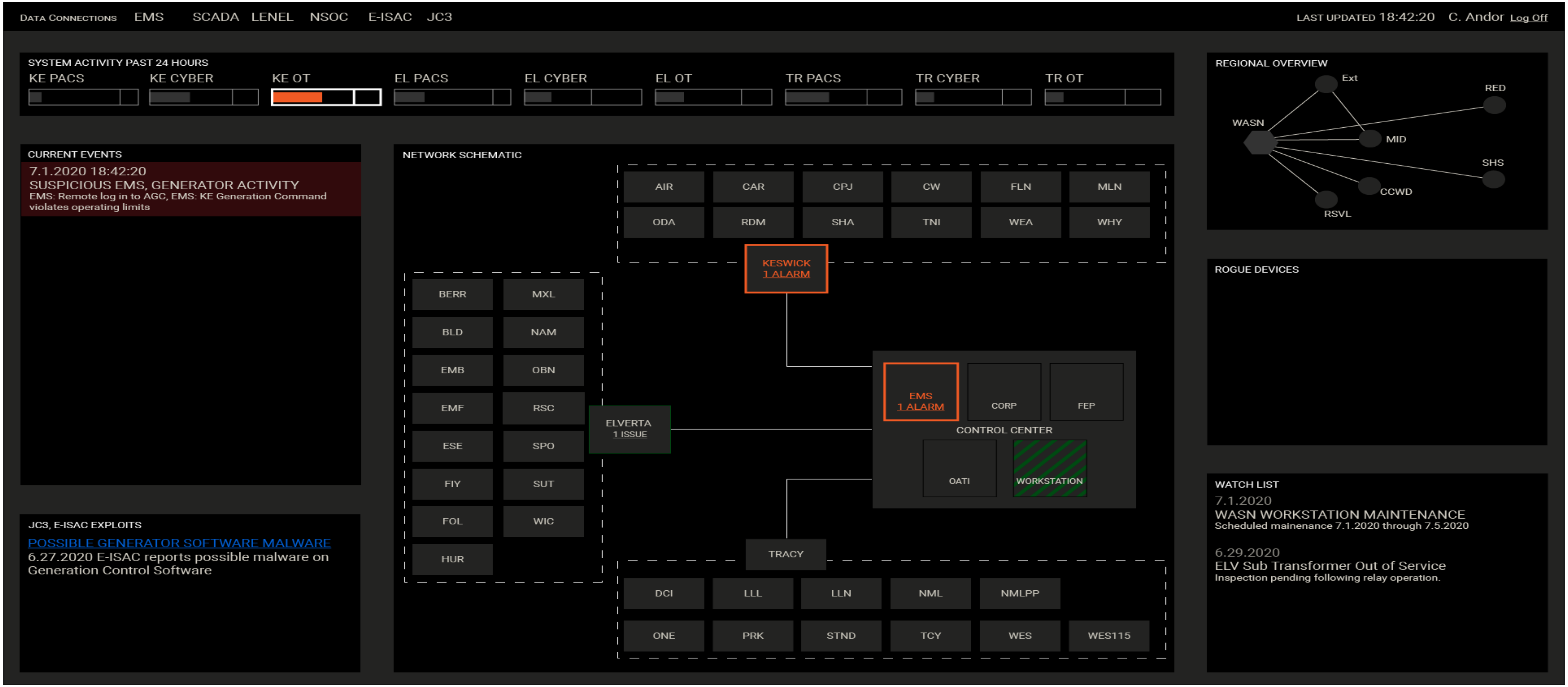

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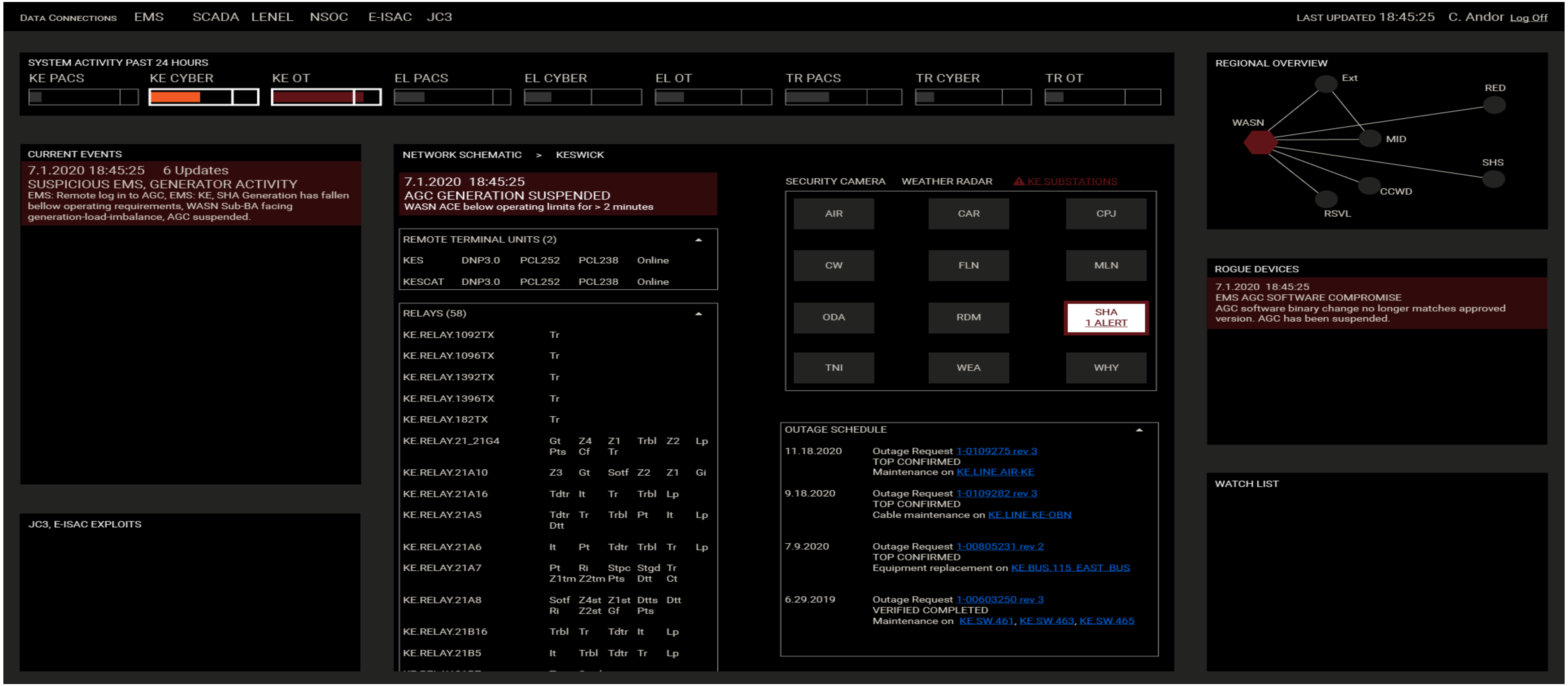
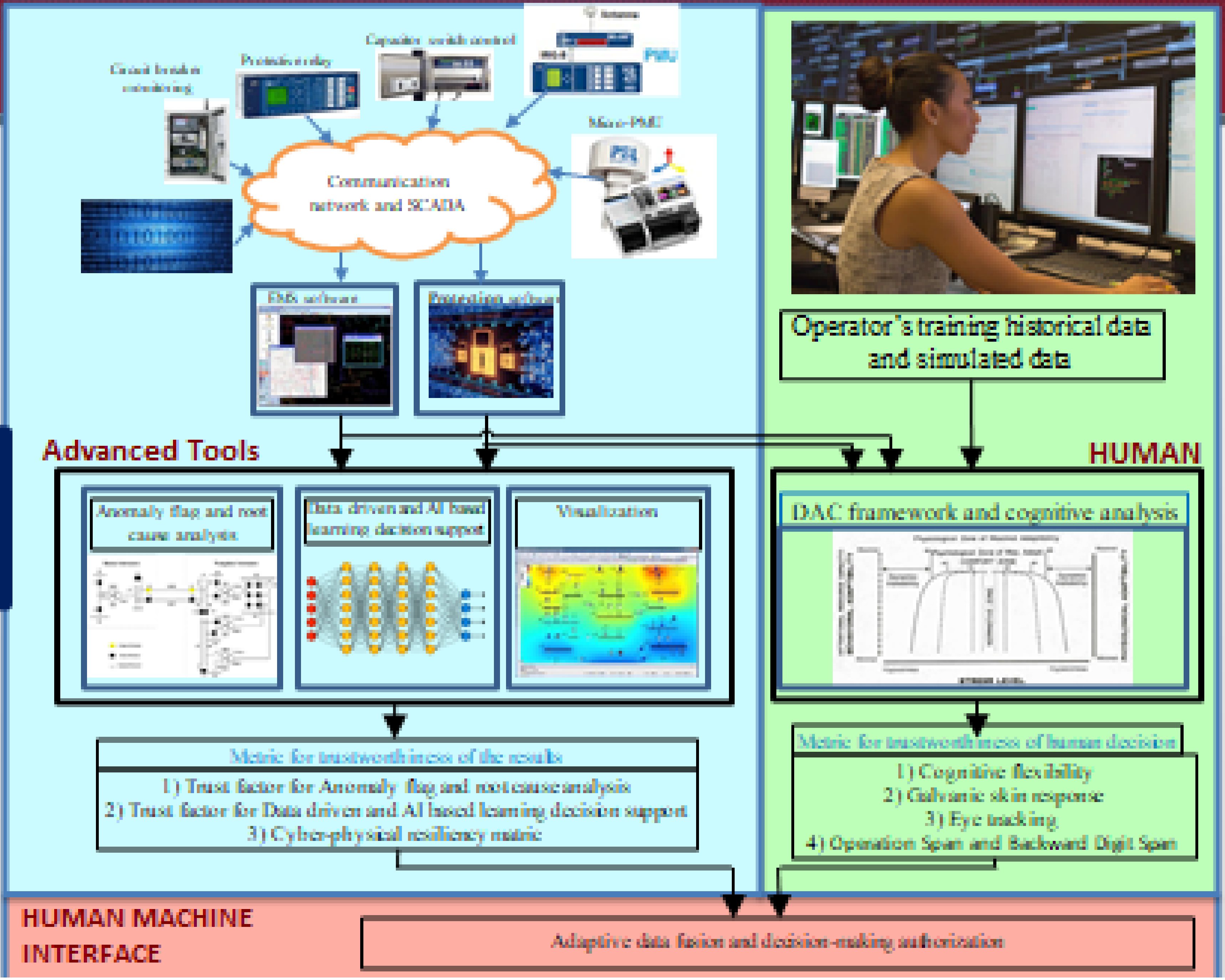


Enabling Power Grid Resiliency: Tools for Operators and Cognitive Analysis

Advanced Tools

- Develop Tools
- Validate in Control Room Environment
- Integrate in Control Room Considering Cognitive Analysis



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Thank you