A Situation Awareness Framework for Designing Effective Interfaces for Smart Buildings

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ABSTRACT

As smart building control systems grow in complexity, their operator displays often become cluttered, overwhelming users with data rather than providing clear insights. This hinders effective monitoring and fault diagnosis. This paper addresses this challenge by proposing a structured framework for designing Building Automation System (BAS) operator displays to support Situation Awareness (SA). The framework translates established human factors theory and related industry resources into a repeatable methodology using three core design elements: universal building interface design principles, a structured set of vocabulary and rules for display structures, and a templated process for high-quality interface content.

Through a series of practical applications, from a real-time controls retrofit to enterprise-level portfolio analytics, this paper demonstrates how the framework can be applied to create clear hierarchical operator displays. The resulting interfaces reduce cognitive load and empower users to quickly move from perception to comprehension to action, enabling faster and more effective decision-making at all levels of an organization.

Introduction

Over the past two decades, "smart building" technologies have embedded digital automation and networked sensing deep into commercial facilities. Despite these advances, persistent underperformance is common and reflective of systemic operator interface issues rather than isolated technical failures. The core problem is that as buildings have become more automated, their BAS operator interfaces have often become more cluttered. With dozens of systems frequently trapped in proprietary silos, operators are flooded with data from inconsistent front-ends, yet are unable to easily translate that data into actionable intelligence. This failure to provide clarity hinders effective building management and optimization.

This paper argues that such operational breakdowns are fundamentally failures of Situation Awareness (SA), the operator's ability to perceive critical information, comprehend its meaning, and project future system states. While SA is a mature concept in other safety-critical domains, it has not been systematically applied to building automation. Current approaches to configuring operator displays often prioritize raw data access over genuine understanding, making it cognitively difficult to diagnose issues or anticipate problems. This challenge directly impacts the workforce, as steep learning curves for complex, non-standard interfaces increase training burdens and frustrate operators.

The remainder of this paper is structured as follows. We first explore how the problem of growing building system complexity hinders operator effectiveness. We then introduce our SA-oriented design framework and its core design elements. Next, we demonstrate the framework's value through a series of practical applications, ranging from real-time control graphics to enterprise-level analytics. The paper concludes with implications for improving operator performance and future research.

The Operational Challenges of Complex and Dynamic Commercial Buildings

Modern commercial buildings are increasingly instrumented and automated, yet their operational performance frequently falls short of expectations. Despite advances in sensors, analytics, and building automation systems (BAS), many facilities continue to consume significantly more energy than predicted or necessary. This persistent gap between expected and actual performance reflects not simply isolated technical failures but deeper mismatches between complex building systems and the human operators responsible for supervising them.

Energy Performance Gap

Commercial buildings represent a substantial portion of U.S. energy consumption, using roughly 13-14 quadrillion Btu annually (approximately 4 trillion kWh) (EIA 2024). Numerous studies have identified substantial opportunities to reduce building energy consumption through improved controls, commissioning, and operational optimization, with reported energy savings commonly on the order of 10-30%, depending on building type, baseline performance, and intervention strategy (King, Perry, and Elliott 2017; Mills 2009; O'Grady, Chong, and Morrison 2021). Even conservative estimates therefore suggest that on the order of one trillion kWh of energy may be unnecessarily consumed annually in commercial buildings. Figure 1 illustrates this "energy performance gap" between actual vs possible building efficiency, highlighting the importance of improving these operational insights.

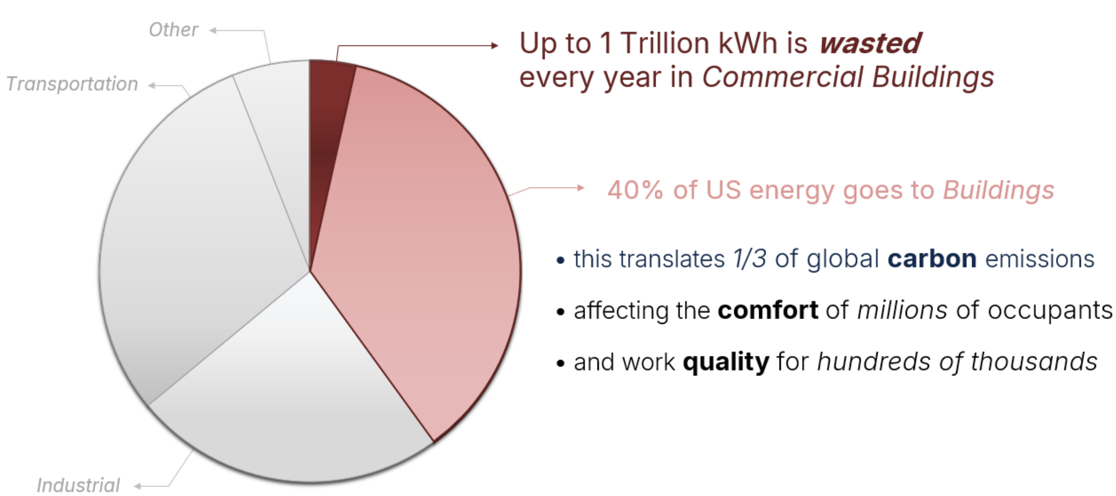

Figure 1. The significance of the building energy performance gap in the U.S. energy system. Commercial buildings consume roughly 4 trillion kWh of electricity annually, and operational improvements represent an energy savings opportunity on the order of one trillion kWh annually. *Sources*: EIA 2024; King et al. 2017; Mills 2009; O'Grady et al. 2021.

In response to the performance gap illustrated in Figure 1, BAS and networked sensors were widely deployed in part to provide more granular operational visibility. In practice, however, the rapid expansion of instrumentation has often produced large volumes of data without the contextual information needed to interpret it. Industry practitioners frequently describe building telemetry as a "digital landfill," where individual values such as temperatures, fan speeds, or valve positions are visible but disconnected from the equipment relationships, served spaces, and control logic that give them operational meaning (Rodgers 2026). As a result, operators may see thousands of data points yet lack the system context required to diagnose inefficiencies, validate performance, or anticipate system behavior. The persistence of the energy performance gap therefore reflects not simply insufficient data, but the difficulty of translating increasingly complex building telemetry into actionable operational understanding.

Growing Complexities

While increasing instrumentation was intended to improve operational insight, it has also coincided with rapidly growing system complexity. Modern buildings integrate mechanical equipment, digital control logic, enterprise analytics platforms, and networked devices that evolve at different rates over a building's multi-decade lifecycle (Brand 1994). As new technologies such as advanced controls, electrification systems, and grid-interactive capabilities are layered onto existing infrastructure, operators must interpret interactions across multiple subsystems whose relationships are not always transparent.

A related challenge emerges in the design of BAS operator interfaces. As building systems and data streams have expanded, many operator displays have accumulated increasing numbers of visual elements and data points rather than improving clarity. Figure 2 illustrates this progression through three generations of air-handling unit displays. The earliest display emphasizes direct visibility of raw data points. Later versions add additional measurements, status indicators, and graphical effects, substantially increasing the number of displayed elements. The number of displayed data elements grows by roughly 2-3 times across successive interface generations while the underlying physical functional components remain relatively unchanged. Rather than improving interpretability, these additions primarily increase visual density and make it harder for operators to identify the signals that matter most for system performance.

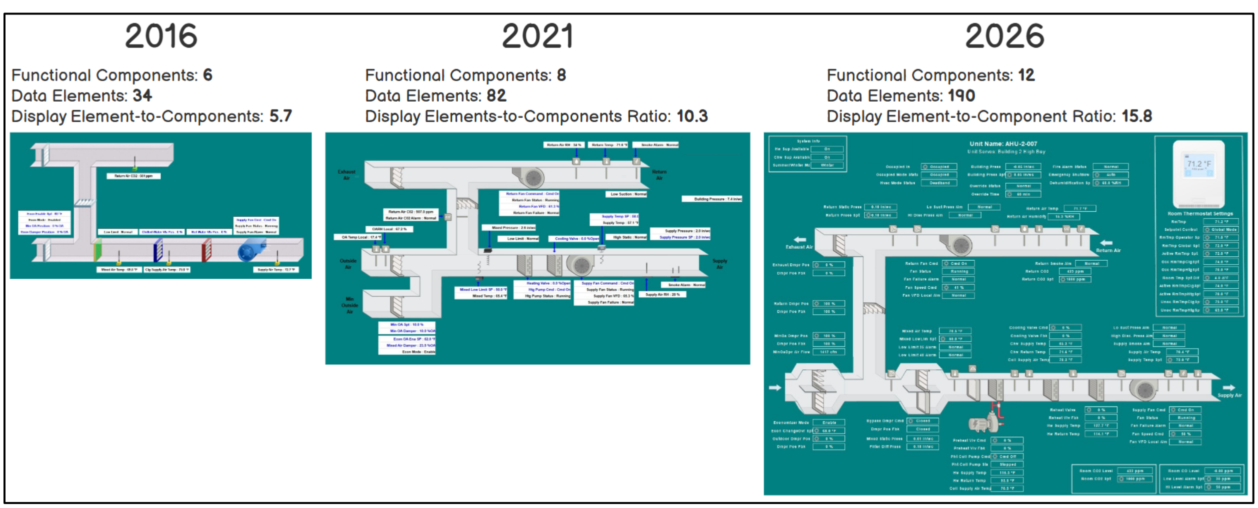

Figure 2. Evolution of BAS displays showing increased data density and visual complexity over successive BAS implementations. *Source*: anonymized federal building projects.

As a result, operators must sift through dense visual environments to locate relevant signals and interpret system behavior. This increase in visual and informational complexity directly challenges the operator's ability to perceive critical information, comprehend system state, and anticipate future performance.

Multidisciplinary Demands

Smart building performance now depends on coordination across engineering, information technology, analytics, and human factors disciplines. As illustrated in Figure 3, modern smart building systems operate at the intersection of three knowledge domains: building engineering, information and data sciences, and human-computer interaction. Buildings are simultaneously physical energy systems, networked digital infrastructures, and operational decision environments. Effective management therefore requires integrating expertise from traditionally separate fields, including mechanical and electrical engineering, software and data architecture, and cognitive and behavioral sciences. The resulting operational environment produces large volumes of heterogeneous data including time-series sensor streams, alarms, configuration parameters, and analytics outputs that must be interpreted by different roles and for different purposes.

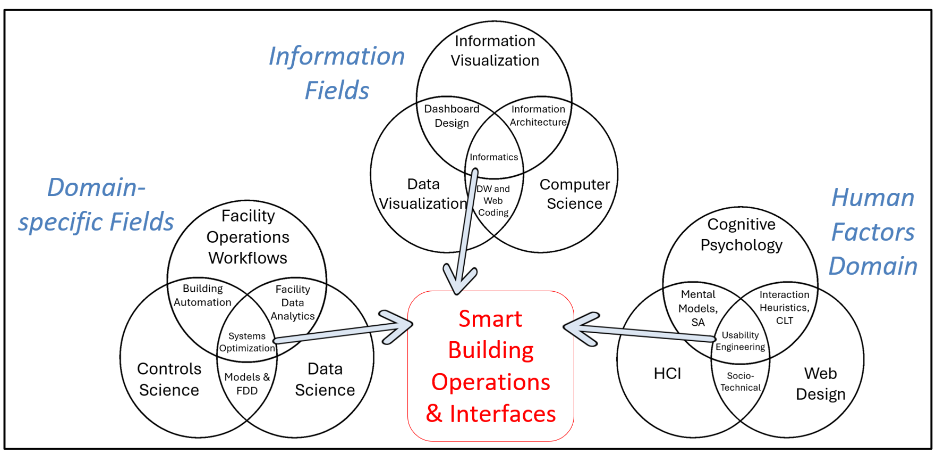

Figure 3. Interdisciplinary foundations of smart building research spanning building engineering, information sciences, and human factors. *Source*: authors.

This multidisciplinary structure often produces operational friction. Facilities engineers typically focus on thermodynamic performance and equipment maintenance, while IT professionals prioritize network security, data governance, and software infrastructure. Vendors and analytics providers add additional layers of complication to platform architecture and related data models. As a result, critical contextual information about building systems is frequently fragmented across tools, organizations, and technical disciplines. No single stakeholder maintains a complete understanding of system behavior, making it difficult to establish a shared operational picture of building performance. These challenges highlight the need for a framework that helps organize complex system information and align interface design with the cognitive processes used to understand building behavior.

A Situation Awareness Framework for Smart Building Interfaces

A cognitive framework is needed to organize the high-complexity and multidisciplinary buildings domain and to guide the design of effective operational interfaces. Several human-systems frameworks address sensemaking in complex environments, including Ecological Interface Design (Vicente and Rasmussen 1992), Naturalistic Decision Making (Klein 1998), and related Cognitive Work Analysis approaches. While these frameworks have been applied successfully in domains such as process control, aviation, and emergency response, the buildings domain presents a distinct combination of continuous monitoring, infrequent but consequential interventions, and heterogeneous operator expertise. This work adopts SA as the primary organizing framework because it directly links interface design to operators' ability to perceive, comprehend, and anticipate system behavior in these complex supervisory environments.

SA as a Theoretical Cognitive Model

Endsley (1995) defines SA as the knowledge state that supports effective decision making in dynamic environments. SA is structured around three hierarchical levels: *perception* of relevant environmental elements (Level 1), *comprehension* of their meaning in relation to goals and system state (Level 2), and *projection* of future system status (Level 3). Originally developed to explain human performance in aviation and military command environments, the model highlights how operators must integrate heterogeneous information sources to maintain an accurate understanding of evolving conditions.

As illustrated in Figure 4, SA functions as an intermediary between the external system state and operator decisions and actions. Individual cognition, experience, and organizational context shape this awareness, while system design (including interface structure, information salience, and automation behavior) strongly influences what information operators notice and how effectively they interpret it. These characteristics make the framework well suited to supervisory building control, where operators must interpret distributed information streams over long operational time horizons.

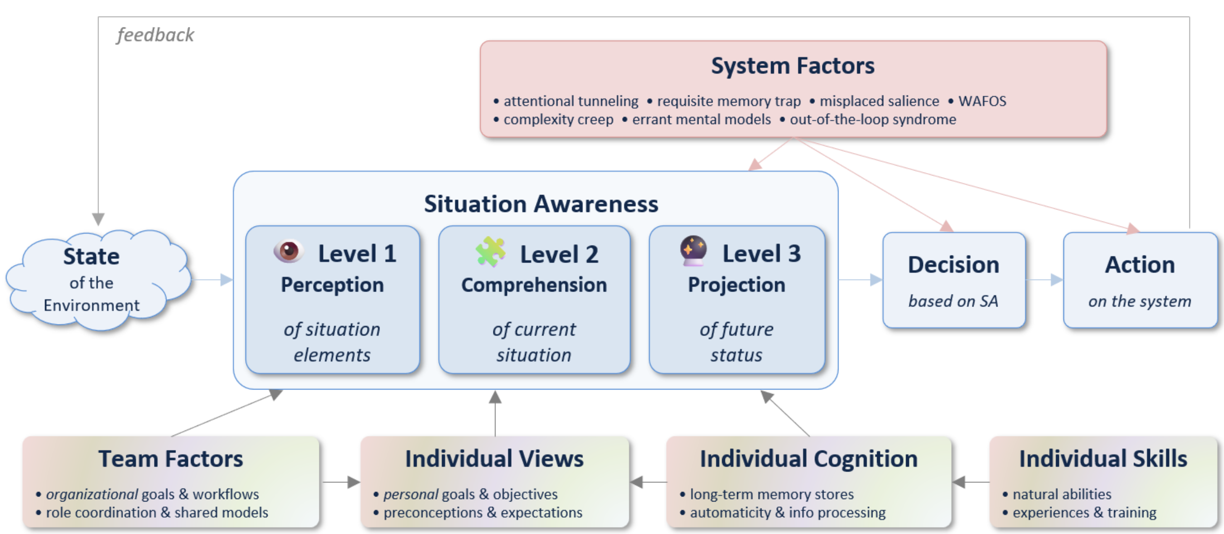

Figure 4. Situation Awareness model, illustrating the relationship between system state, operator awareness, and decision making in dynamic environments. *Source*: author adaptation of Endsley (1995).

SA Challenges in Buildings

Building automation systems operate primarily under supervisory control: automated logic executes continuously while operators monitor system behavior and intervene when deviations occur. Operators rarely manipulate physical processes directly; instead they supervise complex systems through displays, trends, alarms, and analytics dashboards. In this environment, operational challenges often stem from difficulty integrating distributed information, interpreting system modes, and understanding how upstream demand conditions impact system response. Academic (O'Grady, Chong, and Morrison 2021), practitioner (Underhill and Taasevigen 2019), and national laboratory (Mills 2009) studies of BAS implementation and operation have consistently identified system complexity, fragmented data interpretation, and limited transparency into control logic as persistent barriers to effective building performance management.

SA concepts have been applied as organizing frameworks in several supervisory domains including nuclear power, military command systems, and healthcare, where operators must integrate heterogeneous data streams and anticipate system behavior under automation (Endsley 1995). These studies show that breakdowns in perception, comprehension, or projection often arise from interface design choices that fragment information or obscure system relationships.

Table 1 summarizes key Situation Awareness challenges in the buildings domain, organized by SA level, and illustrates how prevailing BAS interface patterns contribute to breakdowns in perception, comprehension, and projection across different user roles and operational timescales.

Table 1. SA Challenges in Buildings

SA Challenge	Buildings Domain Manifestation	Operational Consequence
Data Overload	"Digital Landfill" of extensive raw time-series data with lack of context or prioritization	Slower diagnosis and difficulty identifying relevant signals or insights
Attentional Narrowing	Localized focus on a single variable or alert without system-level context	Symptom-level intervention and missed upstream causes
Misplaced Salience	Visual emphasis based on magnitude rather than operational risk or constraint state	Incorrect prioritization of issues
Apparent Complexity	Mixed orientation, configuration, and control tuning elements on the same display; distributed information across disconnected screens	High cognitive load and weakened mental model coherence
Incomplete or Errant Mental Models	System modes, reset strategies, attributive data, and causal relationships not clearly visible	Misunderstood system configurations and intent leading to inappropriate actions

Out-of-the-Loop Conditions	Automation intent, patterns, and projections are obscured	Surprise system behavior and delayed intervention
Uncertainty and Data Ambiguity	Data gaps and missing indications of data quality, applicability, or reliability	Overconfidence in unreliable or faulty data, and mistrust from missing or questionable data

Designing for SA in Smart Buildings

Within the buildings domain, SA concepts have been applied selectively in areas such as Building Information Modeling (Irizarry et al. 2013) and facilities management analysis (Jodawat 2024). However, these efforts rarely translate SA theory into structured interface design for live BAS. To bridge this gap, this work draws on Endsley's *Designing for Situation Awareness* (2004), which emphasizes deriving domain-specific interface requirements from operator goals, decisions, and associated information needs rather than from available data points.

Supervisory building control is inherently goal-driven. Operators, energy managers, and facility leaders act in support of layered objectives that include maintaining performance, managing operational risk, and optimizing resource use. While the precise articulation of these goals varies by organization, the hierarchical structure of goal decomposition into actionable subgoals is consistent across contexts. Figure 5 illustrates an example supervisory goal hierarchy for general BAS operators. This goal structure forms the foundation for the three design elements proposed in this work.

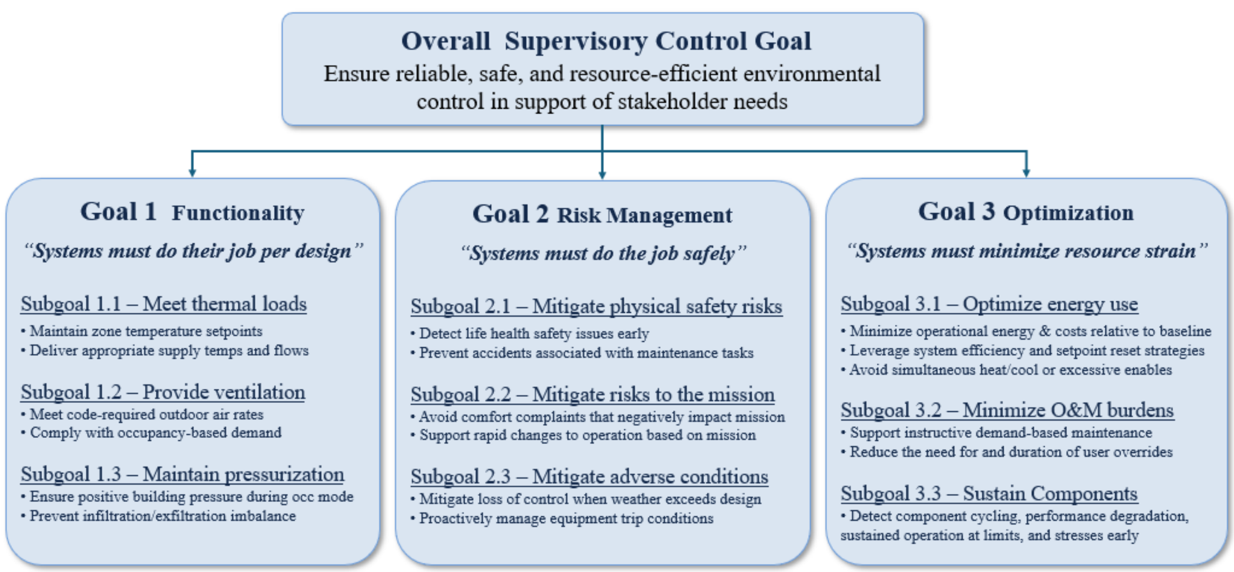

Figure 5. Example Goal and Subgoal Structure for Supervisory Building System Control. *Source*: authors.

Design Element 1 – Supervisory Building Control Principles

Design element 1 translates supervisory decision requirements into actionable interface principles grounded in SA theory. Instead of organizing displays around equipment taxonomies or raw data points, supervisory interfaces should support perception of system state (SA Level 1), comprehension of control relationships (SA Level 2), and projection of future performance or risk (SA Level 3).

Table 2. SA-oriented Design Principles

SA Level	#	Principle	Application
Level 1: Perception	1	Mode Transparency	Active operating modes, overrides, reset states, and constraint conditions must be explicitly visible and clearly differentiated.
	2	Alarm–Context Integration	Alarms should be embedded within functional system context rather than isolated lists, supporting immediate understanding of cause and impact.
	3	Salience Aligned to Operational Risk	Visual emphasis (color, contrast, size) should correspond to operational significance and performance impact, not mere data change.
	4	Consistent Display Grammar	Symbols, color rules, layout conventions, and trend formatting should be standardized across systems and facilities to reduce cognitive friction.
Level 2: Comprehension	5	Goal-Anchored Organization	Displays should be structured around supervisory goals and decision requirements rather than equipment taxonomies or raw point lists.
	6	Representation of Control Intent	Interfaces should expose control logic relationships (e.g., reset drivers, constraint hierarchy, mode logic) rather than only resulting values.
	7	Role-Appropriate Abstraction	Abstraction depth should align with supervisory monitoring, diagnostic evaluation, and configuration tasks.
	8	Progressive Disclosure	Information density and causal detail should increase with navigation depth to support deeper reasoning without overloading overview levels.
Level 3: Projection	9	Structured Trend Context	Trend views should be preconfigured around control loops and operational hypotheses rather than retrieved as generic point histories.
	10	Support for Projection	Interfaces should enable evaluation of trajectory, constraint proximity, and likely future states (e.g., slope indicators, reset limits, demand drivers).

Design Element 2 – Structural Patterns

Design element 2 operationalizes the SA principles introduced in design element 1 through a structured display architecture. Rather than defining interfaces ad hoc around equipment taxonomies or available data points, supervisory displays are organized using a modified ANSI/ISA-101.01 display hierarchy (portfolio, building, system, subsystem, diagnostics). This international standard was developed for process control environments explicitly grounded in human-factors research on operator cognition and Situation Awareness (ANSI/ISA 2015).

Adopting this hierarchy provides a disciplined structural backbone that constrains layout scope, information density, and navigation depth across supervisory levels.

Within this hierarchy, a bounded vocabulary of reusable display regions defines the cognitive workspaces available within each screen, including orientation views, status summaries, structural schematics, temporal evidence (trends), and configuration workspaces. These regions remain independent of system-specific content or visual encoding and instead represent functional information roles within supervisory control interfaces. A complementary set of structural rules governs how regions may be combined and linked across display levels, including progressive disclosure, structural primacy, scope consistency, region boundedness, anchored navigation, context preservation, and causal separation.

Figure 6 illustrates this display grammar, showing the ANSI/ISA-101.01-aligned display hierarchy and the allowable region types that can appear at each supervisory level.

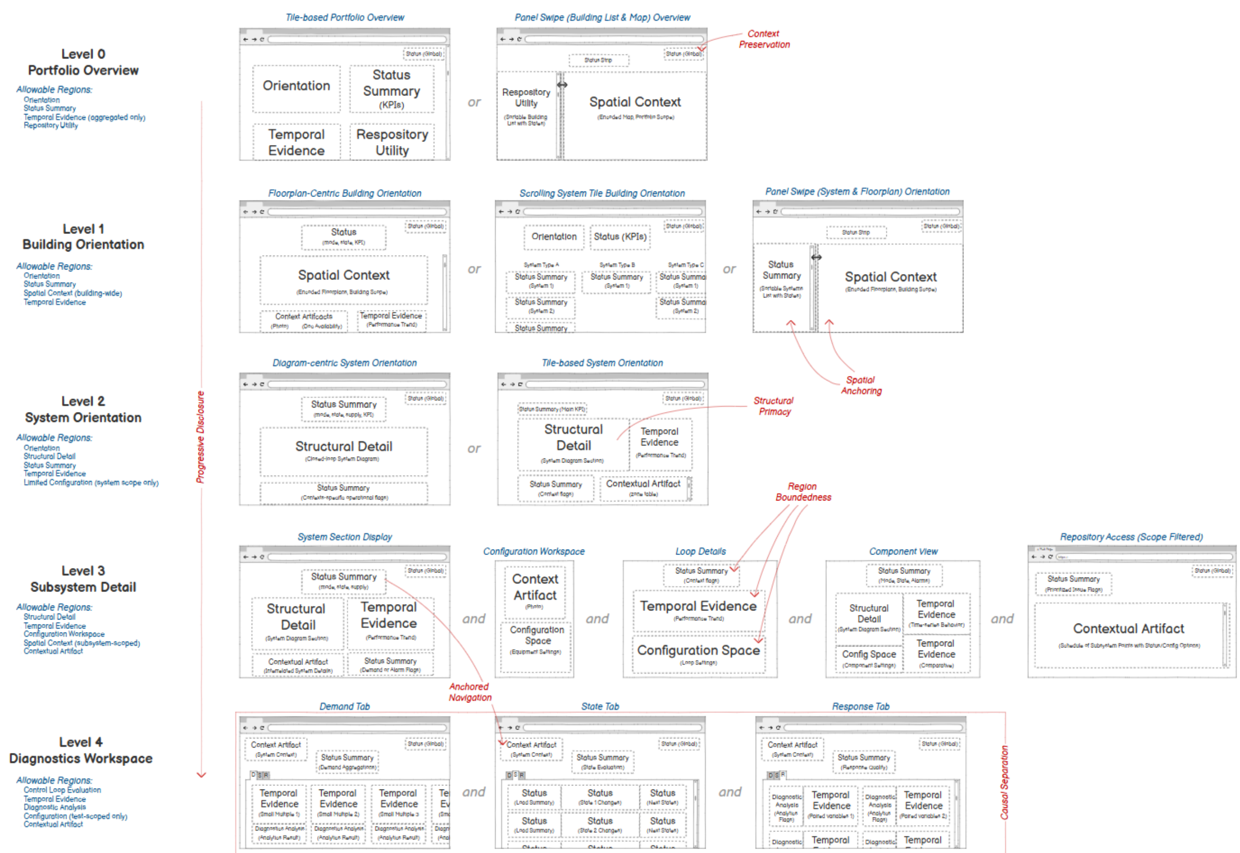

Figure 6. Structural Display Backbone and Region Grammar for Supervisory BAS interfaces. *Source*: authors.

As illustrated in Figure 6, progressive disclosure governs information density as users move from portfolio-level monitoring to subsystem diagnostics, while structural primacy maintains schematic orientation as the dominant element at monitoring levels. Region boundedness ensures each screen contains distinct cognitive workspaces, and anchored navigation preserves context across transitions. Together these rules create an ANSI-101 skeleton that links high-level supervisory design principles to concrete BAS interface implementations.

Design Element 3 – Templated Plans

Design element 3 instantiates the structural vocabulary defined in Element 2 as reusable display templates. Whereas element 2 defines the allowable region compositions and navigation structure, element 3 translates those constraints into standardized layout plans that can be repeatedly applied across HVAC systems and facilities. Each template is therefore derived from an approved region composition at a given supervisory level (e.g., System Orientation or Subsystem Detail) and preserves the structural rules of progressive disclosure, structural primacy, anchored navigation, scope consistency, and region boundedness.

Within each template, regions act as fixed display regions (structural containers) while their contents remain parameterized. Structural Detail, Temporal Evidence, and Configuration Workspace regions maintain consistent spatial relationships but bind to system-specific variables and control relationships. For example, a Subsystem Detail template may always include a Structural Detail region paired with a Configuration Workspace region; however, the specific bindings such as economizer dampers, SAT reset limits, or thermostat parameters vary by application. This separation between invariant structure and variable content enables cognitive consistency across deployments while supporting diverse HVAC configurations.

Figure 7 illustrates how these templates instantiate across supervisory levels using the 2026 air-handling unit example from Figure 2. The Level 2 System Orientation display emphasizes schematic structure, supported by Status Summary, Demand, and Temporal Evidence regions. From this overview, progressive disclosure leads to Level 3 subsystem displays that expose either component structure (economizer) or configuration workspaces (thermostat settings). While the underlying content varies, the structural arrangement remains consistent across views.

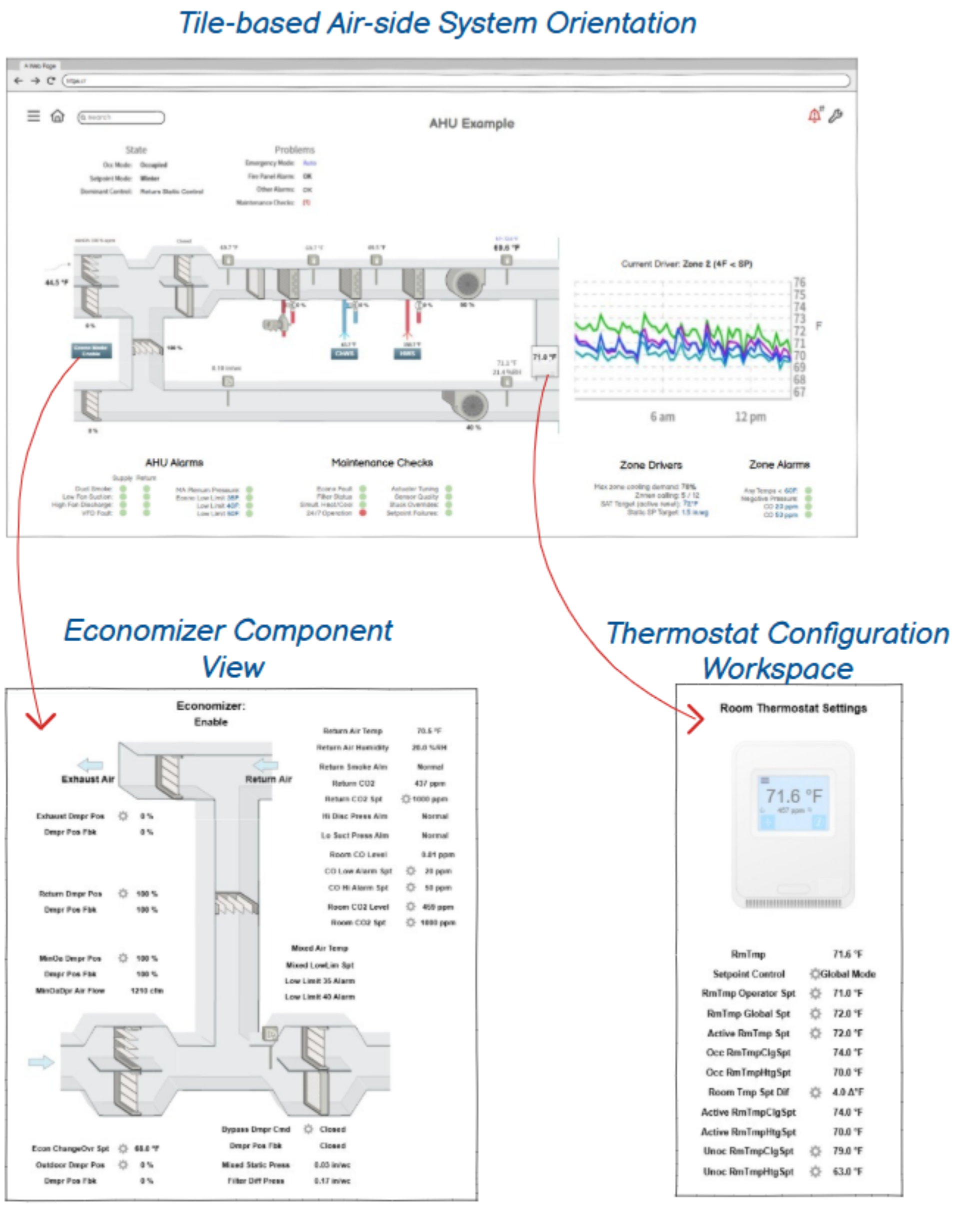

Figure 7. Template instantiation across supervisory levels demonstrating progressive disclosure from system orientation to subsystem detail. *Source*: authors.

Beyond layout consistency, templated plans provide a mechanism for governance and quality assurance. Because templates derive from constrained region compositions, structural compliance can be evaluated independently of equipment-specific content. In practice this reduces variability across buildings, shortens deployment time, and prevents interface fragmentation that forces operators to relearn navigation across systems.

The Practical Applications of SA-oriented Smart Building Design

To demonstrate how the proposed framework translates from theory to practice, this section presents three applied examples spanning operational, system, and enterprise scales of smart building management. Each example illustrates how the SA design principles and structural patterns described in Section 2 can be implemented in real BAS environments. The figures highlight how hierarchical display levels, bounded information regions, and progressive disclosure support operator perception, comprehension, and projection across different supervisory roles. Together these examples show how SA-oriented interface design can improve interpretability and decision support in modern smart building systems.

SA Embedded into a Controls Retrofit of a Single System

The first application demonstrates how the framework can be applied in a retrofitted Chilled Water System (ChWS), moving from a subsystem overview to a specific piece of equipment. Retrofitted BAS environments often suffer from fragmented interfaces and inconsistent visualization practices, making them a useful test case for SA-oriented design.

The Level 2 display shown in Figure 8 presents a system-oriented overview designed to support operator SA within the chilled water plant. The clear process flow and prominent KPIs (e.g., kW/Ton, Load) facilitate perception (Level 1 SA). By synthesizing these data points and comparing them to their setpoints, an operator achieves comprehension of the system's overall efficiency (Level 2 SA), a best practice seen in other expert display visualizations (Anderson 2024). When additional investigation is required, operators can navigate from the Level 2 overview to the Level 3 equipment display also shown in Figure 8. This deeper view provides detailed information for a single piece of equipment (in this case, Chiller 1). Here, the operator can see equipment-specific parameters like load profile analysis and faults spanning high condenser pressure to low evaporator differential temperature. This focused view eliminates clutter and allows the operator to diagnose issues or fine-tune performance for that specific asset, directly enabling Projection (Level 3 SA) of equipment health and preventing potential failures.

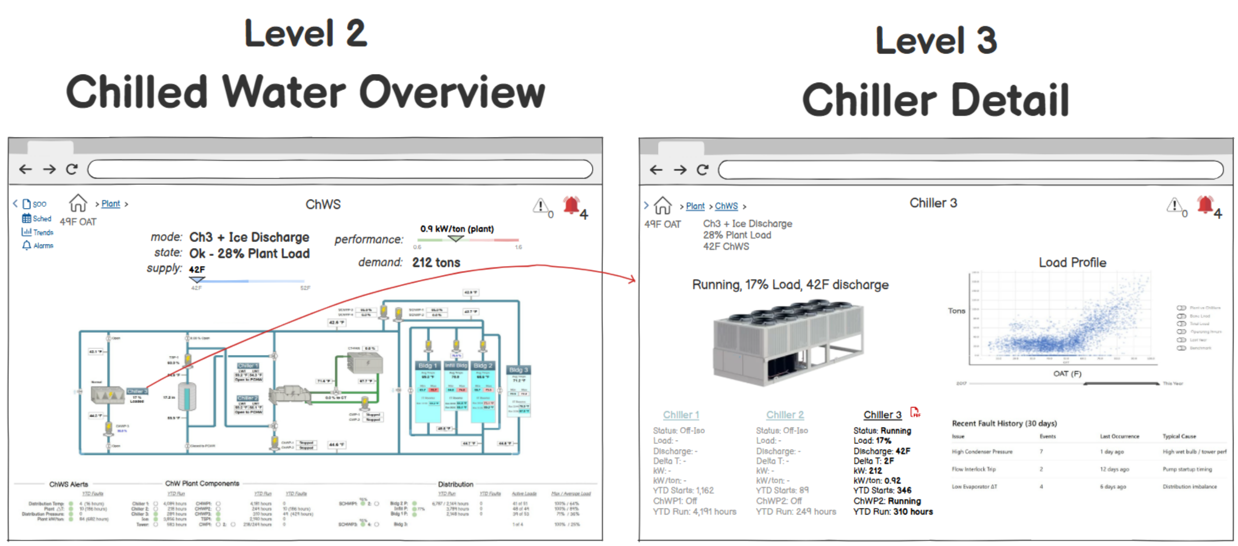

Figure 8. SA-oriented hierarchical displays for a retrofitted chilled water system showing Level 2 system overview and Level 3 equipment detail. *Source*: authors.

SA in New Construction with Multiple Integrated Systems

The second application demonstrates the framework's scalability in a new building construction with multiple, integrated building systems. In these settings, operators must maintain awareness across several interacting HVAC and other systems, making hierarchical display structures particularly important. As shown in Figure 9, the operator's workflow begins at the Level 1 system orientation display, which provides a holistic view of all major building systems, including chilled water, heating water, and air handling units. This display is designed for rapid perception and comprehension, using simple status indicators to show the health of each subsystem. Operators can effectively monitor their entire area of responsibility at a glance and progressively direct attention and action to needed system operations.

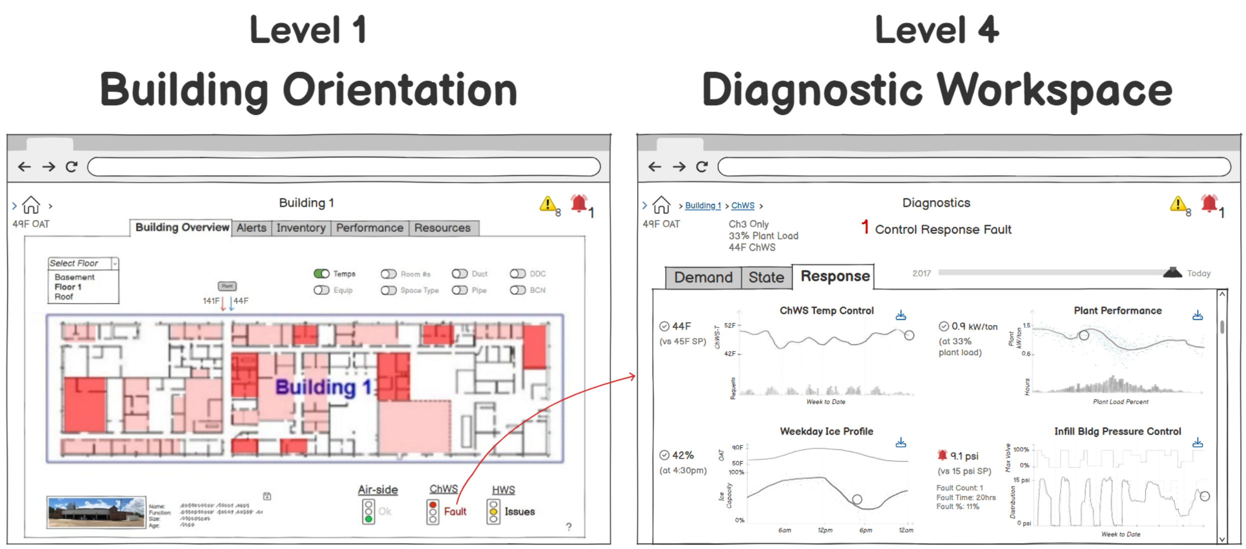

Figure 9. Hierarchical supervisory displays illustrating Level 1 system overview and Level 4 diagnostic detail within an integrated building automation system. *Source*: authors.

If the ChWS were to show an "Abnormal" status, operators can progressively navigate through the Level 2 and Level 3 displays to investigate the issue. If the root cause was suspected to be a control loop problem, they would proceed to a Level 4 Diagnostic Detail regions, such as those illustrated in Figure 9's "Response" tab. This expert-level screen provides detailed information on real-time and aggregated relationships of key control loop variables necessary to perform advanced troubleshooting and optimization. By deferring this complexity until it is explicitly needed, the design avoids information overload and allows specialists to achieve deep comprehension and projection (Levels 2 and 3 SA) for a specific component without distracting the operator during normal operations.

SA in Enterprise Smart Building Environments

The final application extends the framework's scalability beyond real-time control to building analytics environments, which are critical for strategic decision-making. Figure 10 illustrates the top of the information hierarchy by showing a Level 0 dashboard used for portfolio management and the subsequent progressive disclosure to a Level 2 building analytics display.

The Level 0 Enterprise Portfolio Dashboard provides a consolidated view of an entire building portfolio, translating complex operational data into actionable business intelligence. This display is tailored for a portfolio manager or executive, supporting strategic SA. An executive can achieve perception by instantly identifying an underperforming site or building, with anchored views that link status details to spatial or temporal views. The tabbed view then allows for deeper comprehension; the "Issues" tab pinpoints the highest-priority faults across the portfolio, while the "Buildings" tab would provide context by ranking facilities by their Energy Efficiency Score or other KPI context. This enables projection of future costs and helps direct resources to the assets with the greatest need.

From the enterprise overview, a user can navigate to the Level 2 Building Analytics Dashboard for a detailed look at a specific facility. This view is designed for an energy manager, engineer or technician, answering not just that the building is inefficient, but why. By breaking down energy consumption by system and providing a detailed list of faults and their cost impacts, the dashboard provides the granular information needed to diagnose issues, dispatch resources and create project plans. This seamless transition from a high-level business intelligence view (Level 0) to a detailed analytical view (Level 2) demonstrates how the principles of a structured information hierarchy are essential for transforming raw data into effective, data-driven action at all levels of an organization.

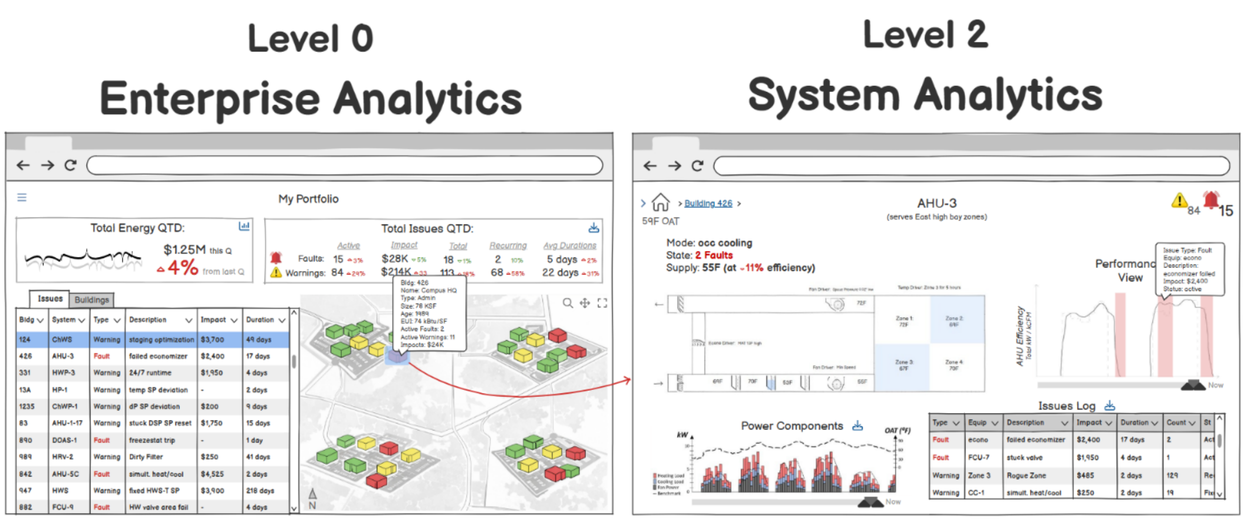

Figure 10. Enterprise-level smart building dashboard demonstrating hierarchical navigation from portfolio awareness (Level 0) to building-level analytics (Level 2). *Source*: authors.

Across these examples, the framework's hierarchical display architecture and structural patterns demonstrate how SA principles can be translated into practical smart building interfaces that support decision-making from equipment diagnostics to enterprise portfolio management.

Conclusion

Building automation system interfaces have evolved toward increasingly dense displays of data points, yet this expansion of instrumentation has not consistently improved operator Situation Awareness. This paper presented a design framework for BAS interfaces structured around three design elements: hierarchical display levels, functional layout of system components, and disciplined data encoding. The framework draws on principles from Situation Awareness research and human-computer interaction to address the growing gap between available data and actionable operational insight.

The proposed approach aims to support progressive disclosure of information, clearer mapping between building system structure and interface representation, and more deliberate prioritization of operational cues.

Future work should test these concepts through usability studies with facility operators and through pilot implementations in real BAS platforms. Experimental evaluations should measure task completion time, fault detection accuracy, and operator workload across alternative interface designs. Field pilots in operational buildings would also help evaluate how display structures supporting SA influence maintenance workflows, diagnostics, and long-term energy performance.

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