Ecological Interface Design in the Nuclear Domain: An Application to the Secondary Subsystems of a Boiling Water Reactor Plant Simulator

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***Abstract*—Accident investigations have revealed that unanticipated events are often precursors of major accidents. Unfortunately, conventional approaches to interface design for complex systems do not explicitly support problem solving during unanticipated events. Ecological Interface Design (EID) is a theoretical framework for designing computer interfaces that explicitly aims to support worker adaptation, especially during unanticipated events, leading to more robust user interfaces. However, limited verification and validation research in representative settings is impeding the adoption of the EID framework in the nuclear domain. This article presents an example by applying EID to the secondary side of a boiling water reactor plant simulator. The interface designers constructed abstraction hierarchy, causal, and part-whole models to acquire pertinent knowledge of the work domain and designed five ecological displays to represent the plant processes. These displays are analytically shown to contain visualization properties that could support monitoring and diagnosing unanticipated events in accordance to the claims of the EID framework. The analytical evaluation of the visualization features of the displays also illustrates that the EID framework could be applied to improve current verification practice. A companion article reports an empirical evaluation of these ecological displays to validate whether these properties could enhance operator performance.**

***Index Terms*—Control room, ecological interface design, nuclear power plant.**

I. Introduction

LOW carbon emission and stable fuel supplies are rekindling interest in nuclear power [1]–[6]. At the same time, Nuclear Power Plants (NPPs) are undergoing significant modernization to both extend plant lifecycles and accommodate uprates [3], [7], [8]. This period of global and local change presents a unique opportunity for the industry to shift toward advanced technologies, including those that support the cognitive workload challenges of control room operators who hold ultimate responsibility for plant safety and efficiency.

Effective human-system interface design is increasingly acknowledged as necessary to support operators in achieving reliable and safe operation (e.g., [9]–[18]). Knowledge about interface design has been accumulating from both research and practice. Nevertheless, new human-system interfaces developed with this recent knowledge must undergo rigorous verification and validation to ensure safe NPP operations [19], [20].

The US Nuclear Regulator Commission [19] regards verification as an evaluation of whether the properties of a design product conform to regulatory standards and guidelines[1] (also see [21]). Verification is often conducted through analytical means. On the other hand, validation assesses whether the performance of the product is in compliance with operational and safety goals or requirements of the regulators and industry [19], [20]. Validation is often comprised of a series of empirical studies evaluating the verified technologies.

A. Current Analysis Approaches for Interface Design and Types of Verification

In the nuclear domain, human-system interfaces generally undergo two types of verification–(i) human-system interface task support verification and (ii) human factors engineering design verification [19]. Task support verification analytically evaluates whether the interface fulfills the criteria derived from task analyses, which identify information associated with those activities or actions that must be performed in order to meet higher level goals within a specific context [22]. Information identified by task analyses could also form the basis for design; and design approaches that rely primarily on task analysis are deemed "task-based". Task-based approaches to interface design and task support verification together ensure the efficiency of the operator in performing "procedure guided tasks" or well-defined tasks under anticipated situations [23], in which decision making is largely rule-based (see, [19], [24]).

[1]Verification is sometimes more narrowly defined as an assessment of conformance between the final product and the design specification (e.g., [30]). Readers who prefer such a perspective may interpret the content of the article to be more relevant to validation than verification. More specifically, the application of the EID framework could improve validation rather than verification practice.

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Human factors engineering design verification analytically evaluates whether the interface accommodates human capabilities and limitations as reflected by design guidelines (e.g., [21]). Guidelines capture established findings in human factors research, particularly on syntactic issues (e.g., legibility/font size requirements), and reflect knowledge from operational experience (e.g., scale units and labeling specification). Thus, guidelines could directly inform interface design as well as verification. In addition, user-centered design methods that specify information based on operational experience may supplement guidelines to achieve design verification. In essence, guidelines and human factors engineering design verification together ensure that information on the interface is presented adequately for human perception.

B. Unanticipated Events and Knowledge-Based Tasks

The conventional design approaches (i.e., task-based, user-centered, and guideline-driven) and verification processes have seemingly led to interfaces with adequate performance and reasonably good safety records. However, accident investigations indicated that unanticipated, non-routine events are often precursors of serious accidents [14], [25]–[27], in which decision making is mostly knowledge-based. Unfortunately both task analysis and operational experience review do not explicitly and conceptually account for ill-defined tasks and unanticipated events [11], [23].

Control room operators are increasingly challenged by knowledge-based tasks, which are often ill-defined, involve reasoning about safety and operating goals, and managing the sometimes conflicting means of achieving those goals (see, [19]). As frequently occurring tasks become automated, system-wide complexities rise, leaving operators to manage unanticipated, ill-defined tasks [28], [29]. Even monitoring during normal operations is cognitively demanding, sharing many characteristics with active problem solving [29].

While effectively addressing the efficiency and safety concerns associated with procedure-guided and even “operational experience review-identified difficult” tasks [19], conventional design and verification approaches relying on task analysis, operational experience, and guidelines are not explicitly conceptualized to support the reasoning and problem solving that characterize knowledge-based tasks. Given the trend towards knowledge-based work (see e.g., [28]) and lessons learned from past accidents [18], the design and verification processes could be substantially improved if they offered guidance to help operators cope with knowledge-based or ill-defined tasks during unanticipated situations.

C. Work Domain-Based Approaches

Recent research on interface design increasingly emphasizes work domain-based approaches [28], [30]. Work domain-based approaches explicitly aim to support operators in performing ill-defined tasks during unanticipated situations (i.e., knowledge-based tasks; see knowledge-based behavior in [24]). These approaches capture information describing the system structures in terms of their functions within the overall environment or ‘ecology,’ in which the work is to be performed and goals achieved [22]. Over the past decade, several alternative frameworks with similar perspectives have emerged [17], [31]–[33]. In essence, work-domain based approaches seek to improve the robustness of interfaces; that is, their effectiveness in supporting operators in coping with all events, including unanticipated ones [11], [23].

Interfaces generated from work domain-based approaches present information similar to those that are discovered through functional requirement analysis as mandated by regulators. “Functional requirement analysis is the identification of those functions which must be performed to satisfy the plant’s safety objectives” [19]. More specifically, [19] states that a functional requirement analysis is conducted to (1) determine the objectives, performance requirements, and constraints of the design, (2) define high-level functions to accomplish the objectives and desired performance, (3) define relationships between high level functions and plant systems, and (4) provides framework for understanding the role of the controllers[2]. This description reveals that the information discovered through functional requirement analysis coincides with those presented in interfaces following work domain-based approaches which often include purpose, constraint and relationship information on system structures (see [28]).

Though required by regulators for interface design input, functional requirement analysis is only prescribed as a means to specify the roles of operators, thereby setting the criteria for the information content for supporting operators in their respective roles [19]. In contrast, work domain-based approaches explicitly seek to present functional information on interfaces as means to support problem solving during unanticipated events in which pre-defined roles could limit operator adaptability in resolving disturbances.

Work domain-based approaches can theoretically improve current interface design and verification practices to ensure effective operator support for knowledge-based tasks. These approaches also appear viable as the analysis methods generate information that resembles those in functional requirement analysis. However, work domain-based approaches have yet to be widely practiced in industry. One factor precluding industry from gaining the knowledge and confidence necessary to adopt work domain-based approaches is a shortage of design, verification, and validation efforts based on these new interface design concepts. The literature offers very few proof-of-concept examples of work domain-approaches at the scale and complexity of industrial systems, and where examples exist in private industry they are typically protected as intellectual property. Apart from design practice, the literature also provides very few examples in which information identified by work domain-based methods forms the basis for interface design verification. Given the paucity of proof-of-concept examples, there are also virtually no validation studies of work domain-based approaches in process control systems. Consequently, it is unknown whether performance advantages deduced from theories or observed in laboratory environments are obtainable in practical settings.

D. Overview of the Current Study

To address this research issue, the University of Toronto, University of Waterloo and the OECD Halden Reactor Project es-

[2]See [28 Chapter 11] on how Work Domain Analysis might be applied for allocating functions to controllers.

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tablished a research program to assess the utility of a work domain-based approach—Ecological Interface Design (EID)—for the nuclear industry. The intent was to provide representative research results that speak to the selection, development, implementation, verification and validation of human-system interface technologies during upcoming NPP modernization and construction projects.

EID was selected as the work domain-based approach because, among comparable approaches, it offers the most substantial corpus of research available in the literature. Proof-of-concept ecological interfaces have been reported in many domains and empirical support continues to accrue [34]. However, many of these studies are only marginally representative of industrial settings. Still, competing work domain-based approaches offer markedly fewer representative examples and less empirical support. This lack of detailed, representative application, verification, and validation studies in the open literature inhibits knowledge transfer, slowing down industry adoption of work domain-based approaches.

In this article, we report our efforts in designing ecological displays for the secondary side of a high fidelity nuclear plant simulator and verifying the conformance of the ecological displays to the EID framework. In describing the products of the EID framework, we aim to provide guidance and foster confidence in designing ecological displays. In verifying the conformance of the displays to the EID framework, we illustrate the potential contribution of applying work domain-based approaches as part of human-system interface verification to ensure the support of knowledge-based tasks. In a companion article [35], we report on our validation efforts involving an empirical evaluation of the ecological displays.

HAlden Man-machine laboratory BOiling water reactor (HAMBO) [36], [37] was selected as the simulator platform for our research as it is a high-fidelity simulation of an operating, 1200 MW, boiling water reactor (BWR) plant. Developed for realistic testing of prototypes and systems prior to installation, HAMBO is sufficiently advanced and flexible to accommodate the complex, information-intensive graphics that typify ecological displays. It also operates at a scale and complexity comparable to the real plant, addressing concerns about the representativeness of research findings to actual practice. HAMBO has demonstrated high face validity in many previous human-system interface studies employing licensed operators [37]. Thus, the design and verification research on EID described in this article is applicable to the practical settings of nuclear plant operation. The article also provides a necessary foundation for future research, including attempts to validate that EID can deliver practical benefits to the nuclear industry.

The remainder of this article is organized as follows: Section II describes the EID framework and reviews its application to industrial systems. Section III then describes and verifies the products of this study, namely the Work Domain Analysis for the secondary side of the BWR and the ecological displays, themselves. Finally, Section IV discusses contributions and insights gained though development and verification of ecological displays at the scale and fidelity of an operating NPP.

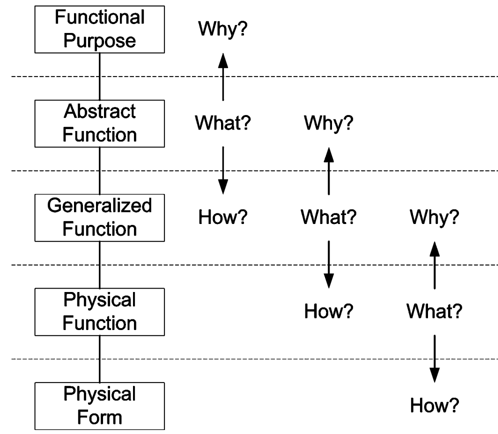

Fig. 1. Five-level abstraction hierarchy with the 'why, what and how' characterization. 88 × 76 mm (600 × 600 DPI).

II. The Ecological Interface Design Framework

EID is a theoretical framework for designing human-computer interfaces for complex socio-technical systems [11], [12]. The EID framework relies on two fundamental activities: (1) defining information content based on psychologically relevant models of the work domain, and (2) representing information based on perceptual forms that are compatible with human cognitive capabilities [11], [12].

The specific tools in the original framework include the Work Domain Analysis, which guides information content and structure; and the Skills, Rules, and Knowledge (SRK) taxonomy, which guides the selection of perceptual form [11], as outlined below. After describing the framework, itself, we review the EID literature to uncover the foundations upon which the design and verification component of our research program is built.

A. *Work Domain Analysis: A Guide to Information Content and Structure*

The Work Domain Analysis consists of an Abstraction Hierarchy (AH) and a Part-Whole description. Together, these descriptions form a structured framework for modeling work domains to discover the constraints, invariants and parameters crucial to problem solving that should be contained within an interface [11], [12], [28], [38].

The abstraction hierarchy is a knowledge representation framework characterized by structural means-ends links between levels (see Fig. 1). The structures are characterized according to their functions; thus, the AH could be a framework for conducting functional requirements analysis to capture information required by regulators. The means-ends links can be conceptualized as 'why, what and how' connections between entities at different levels. This hierarchy enables each level to describe the work domain from a different perspective. Between adjacent tiers, middle tiers represent the structure of the work domain (what), while tiers above explain the purpose (why) and tiers below describe the means (how) [28], [38].

In process control, an AH typically consists of five levels as in Fig. 1: Functional Purpose (FP), Abstract Function (AFn), Generalized Function (GFn), Physical Function (PFn), and Physical

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Form (PFm), shifting from a high-level purpose statement down to a detailed physical description of a system's components [38].

The second component of the WDA is a part-whole decomposition. Decomposition is undertaken to acquire a more detailed technical perspective of the work domain. This portion of the analysis documents the physical components of a system and its aggregates (as units or subsystems).

The degree to which the abstraction hierarchy and part-whole decomposition are populated is at the discretion of the analyst, based on domain complexities and project objectives. As well, other domain analysis tools may be incorporated to supplement the WDA. For this project, a causal analysis is performed within the Abstract Function and Generalized Function levels; the physical connections amongst components and their aggregates are documented in the part-whole analysis (see Section III). These causal and physical connections in the WDA are known as topological links, which depict relationships between system structures within an abstraction level. For recommendations on supplemental modeling tools in process control, see [10], [12].

In summary, WDA identifies constraints, invariants and parameters that are necessary to support knowledge-based tasks. Furthermore, the WDA is a functional analysis that overlaps significantly with the mandatory functional requirement analysis. The multiple representations of functional structures, structural means-ends and topological links in the WDA yield the required information on system objectives, functional requirements, and functions-systems relationships that must be included in the outcome of functional requirement analysis. Given that WDA specifies the information requirements for the interface, it can also serve as the basis for design verification to ensure the support for knowledge-based tasks [39], similar to how task analysis is the foundation for task-based approaches to both interface design and human-system interface task support verification.

B. Skills, Rules, Knowledge Taxonomy: A Guide to Visual Representation

In EID, transforming information content and structure into perceptual forms is guided by the Skills, Rules, Knowledge (SRK) taxonomy [24]. Using this taxonomy, the interface designer can judge whether the perceptual forms convey relevant domain information in a manner that capitalizes on innate human perceptual capabilities.

SRK proposes three mutually exclusive categories of information perception—signals, signs, and symbols. Signals are continuous quantitative indicators of the time-space characteristics of an environment (e.g., visual trajectory of a road). These trigger Skill-Based Behaviors (SBB) marked by sensory-motor performance in the absence of conscious control (e.g., driving along a road).

Signs are familiar labels or percepts with external reference to actions or environmental states (e.g., a stop sign). These initiate Rule-Based Behaviors (RBB) associated with the use of 'stored rules' derived empirically from prior successful experience (e.g., braking in response to a stop sign). For many procedure guided and routine tasks, operators extensively apply RBB.

Symbols are information interpreted as concepts with functional properties (e.g., highway mileage signs) that activate Knowledge-Based Behavior (KBB). This is identified by conscious processing of information through the application of abstract knowledge (e.g., calculating the time to a destination). For knowledge-based tasks, operators apply KBB to diagnose problems and formulate solutions to achieve safety and productivity goals.

SRK connects these information representations (i.e., signals, signs, and symbols) with human levels of cognitive control (i.e., SBB, RBB, and KBB), thereby, providing the basis for predicting performance. Human beings appear predisposed toward the lower level cognitive controls, that is, toward skill- and rule-based behaviors. This propensity suggests that compatibilities with cognition increase if the interface does not demand that operators engage at higher cognitive levels than necessary. Nevertheless, NPP operators engage in all three levels of processing, depending on the demands of the task and the expertise of the operator. Thus, as a general principle, designers should aim to present information in the forms of signals and signs on the interface. This general principle could also serve as a verification criterion to ensure human-interface compatibility.

SRK is just one analytical evaluation tool predicting human compatibilities with representational designs. The literature describes supplementary tools that support form design for ecological interfaces as well. These tools are generally proven perceptual form solutions intended to represent information in certain relational structures, such as those documented in the Visual Thesaurus [12] or the library of representations for Functional Primitives [10].

C. Research on Ecological Interface Design

The outlook for EID application appears promising, especially in the process control domain where the concept originated. The nature of reported proof-of-concept designs is continually more representative of industry practice, and mounting empirical evidence suggests that ecological interfaces contribute to improved operator performance (see [12], [34]). The discussion here focuses on the research pertaining to design examples, leaving the review of empirical work on validating EID to a companion article [35].

1) A Review of the EID Literature: The first ecological interface was developed for a process control 'microworld' simulation—DURESS [40], [41], which has since served as an experimental platform for many laboratory studies. DURESS has also been used as an example to illustrate that EID can serve as an analytical evaluation/verification tool [39]. More recently, Reising and Sanderson [42] designed an ecological interface for another microworld—Pasteurizer. Because both work domains aimed to have a balanced level of complexity that demonstrates the applicability of EID and provides experimental control in laboratory studies, the ecological interfaces for them are not fully representative of industrial processes.

Extending EID beyond microworld applications, Jamieson and Vicente [43] developed an ecological interface for a model petrochemical processing unit. However, the interface was neither based on an operational unit nor implemented in any simulator. More recently, Jamieson [44], [45] developed an ecological interface for an operating acetylene hydrogenation reactor.

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Both interfaces, though, are situated in the petrochemical processing domain.

Applications of EID have been demonstrated in the power generation domain as well. Dinadis and Vicente [46] developed an ecological interface for a conventional feedwater subsystem. However, their scope was limited to a single subsystem of a prototype plant, falling short of the scope and complexity of an operating plant. Burns [47], [48] developed, implemented, and evaluated ecological displays for a prototype fossil fuel power plant, but descriptions of the design in the literature emphasize the methods of information navigation and integration.

Three applications of EID to the nuclear domain have also been reported. Ham and Woon [49], [50] developed an ecological interface for a NPP simulator, but without employing the configural graphics that have typified the visual form of other ecological interfaces. JAERI [51] developed and implemented an ecological interface for a shipboard nuclear power plant simulation. Though representative of industry practice in terms of scale and complexity, the design is not described in sufficient detail in the open literature to serve as a reference for designers. Toshiba [52] has developed and implemented an ecological interface for a full-scale BWR simulator as well. However, the design appears to be an overview display, providing information mostly at high levels of abstraction and excluding components and controls of the plant simulator. In summary, EID research in the power generation industry in general, and the nuclear industry in particular, has shown some promise. However, the design examples are either of insufficient scale and fidelity to demonstrate feasibility of EID for industry, or they are inadequately described to foster confidence in the design framework. In addition, the literature does not contain any applications of EID for improving verification practice beyond its first proposal.

2) Implications for the Nuclear Industry: The paucity of representative studies of EID in the nuclear industry may impede the adoption of the framework in this industry. As noted above, public information that ecological displays can be designed and implemented in NPP settings is in short supply, but is needed to persuade management and guide practitioners. Furthermore, applying EID for verification purposes to ensure the support for knowledge-based tasks is virtually non-existent. EID research must begin to address these challenges if its proponents hope to make inroads in the nuclear industry.

III. EID FOR THE SECONDARY SIDE OF A BWR: ANALYSIS AND DESIGN

We have developed a work domain model and ecological displays for the secondary side of a BWR plant. The analysis, design, and verification effort was distributed amongst the three research groups by separating the secondary side into turbine, condenser, and feedwater divisions, according to processes of the Rankine cycle.

The turbine division carries out the isentropic steam expansion supported by equipment between the discharge points of the reactor and low-pressure turbines. The condenser division performs the isobaric heat rejection containing condenser-related and off-gases discharge subsystems. The feedwater division executes the isentropic compression and regeneration (i.e., preheating) of water, handled by equipment between the points of condensate discharge at the condenser hotwell and feedwater entry at the reactor.

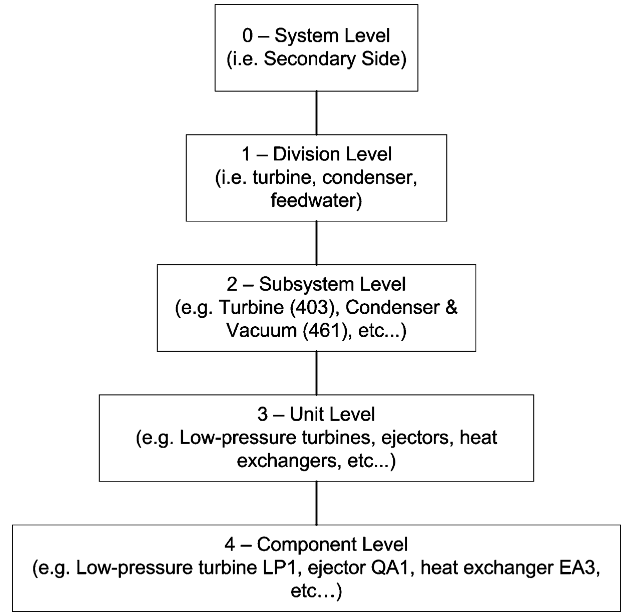

Fig. 2. Levels of part-whole decomposition. 88 × 88 mm (600 × 600 DPI).

A. Work Domain Analysis

The scale of this analysis does not permit a full description here. Instead, we present several parts to illustrate key characteristics and functions.

1) Part-Whole Models: The part-whole models provide views of the system at different levels of detail. These levels of decomposition are: (0) system, (1) division, (2) subsystem, (3) unit, and (4) component (Fig. 2). Level 0 represents the entire secondary side of the plant, treating it as a single black box with specified inputs and outputs (Fig. 3). At Level 1, the part-whole models represent each division as a black box and illustrate inputs and outputs (e.g., Fig. 4). Level 2 part-whole models open up each black box to examine inputs, outputs, and physical connections of the subsystems. (e.g., Fig. 5). The decomposition continues at Level 3 examining the inputs, outputs, and physical interconnections amongst units in each subsystem. Level 4, the lowest level of part-whole decomposition, provides details at the component level and resembles a piping and instrumentation diagram. This level of part-whole models was developed for the Feedwater division only because the Level 3 representation was not sufficiently detailed to capture the parallel operations of components[3].

2) Abstraction Hierarchy Models: An AH model integrated with causal descriptions was developed for Levels 1 through 3 of the part-whole models. Each of the AH models consists of four

[3]The feedwater division is unique in comparison to the other two divisions. In the turbine and condenser divisions, parallel equipment serves to provide redundancy. Thus, the interaction between components in parallel streams is not significant. In contrast, much of the equipment in the feedwater division is operated in parallel during normal operations. This distinction necessitated further analysis at the component level to inform interface design.

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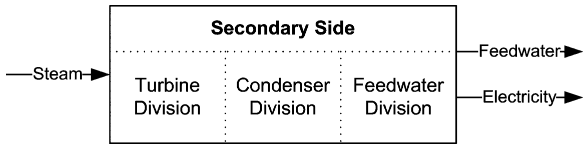

Fig. 3. Part-whole model of the secondary side of the simulator plant (i.e., Level 0 decomposition). 88 × 25 mm (600 × 600 DPI).

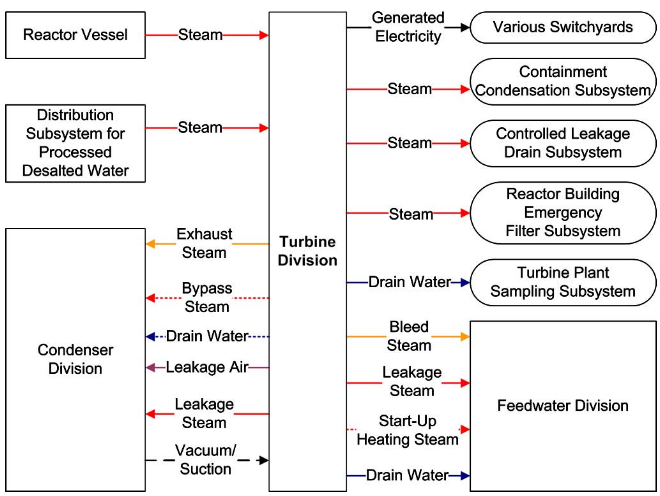

Fig. 4. Part-whole model of the turbine division at Level 1 decomposition (i.e., division black box level). Subsystems listed above exist in the operating nuclear plant but are not part of the simulator. 88 × 67 mm (600 × 600 DPI).

abstraction levels—Functional Purpose (FP), Abstraction Function (AFn), Generalized Function (GFn), and Physical Function (PFn)[4].

For the purposes of illustration, the AH model of the condenser division at the subsystem level is presented (Fig. 6). The FP captures the purposes of all subsystems within that division. For example, one key purpose of the condenser division is to satisfy the condensate demand of the feedwater division (as indicated by the second item from left at the FP in Fig. 6). The means-ends links (blue dotted lines between levels in Fig. 6) point to physical laws or first principles at the AFn to achieve this purpose. These first principles can be summarized as conservation of energy and mass.

To satisfy the condensate demand of feedwater division requires mass source, transfer, transformation, and storage functions. The same purpose also requires energy transfer that, in turn, depends on the first and second laws of thermodynamics.

The manipulation of mass and energy at the AFn level is achieved by means of engineered processes at the GFn level. With respect to the physical laws linked to satisfying condensate demand, the means-ends links indicate that the mass source is "Steam Supply 1" transferred as a result of "Suction" and "Vacuum Generation" (i.e., low pressure). The energy transfer is connected to "Heat Conduction/Cooling" and "Condensation"; the mass transformation is also linked to "Condensation." The condensate mass is stored in a "Condensate/Particulate Inventory".

[4]The Physical Form layer is omitted because the simulator environment does not account for location and appearance.

The processes at the GFn are carried out by specific plant subsystems at the PFn level. Continuing with the purpose of satisfying condensate demand, the means of steam supply are provided by the Turbine System (403), while the means of suction, heat conduction, condensation, and inventory are provided by the Main Cooling Water System (441), and Condenser and Vacuum System (461).

3) Causal Relationships: In addition to means-ends relations between levels, this model represents causal links that illustrate structural relationships within the abstract function and generalized function levels[5]. To demonstrate how these links complement means-ends relations, we describe the causal relationships for the GFn level in Fig. 6.

Starting from the left, steam supplies are drawn into the condenser division by suction and (at center) vacuum generation. These gases then undergo heat conduction/cooling and non-condensable gas extraction simultaneously. The condensable gases (mainly steam) condense after cooling, generating a vacuum and contributing to condensate inventory at the condenser hotwell. The condensate inventory is eventually discharged (into the feedwater division). The non-condensable gases are diverted to the off-gas systems for treatment. First, some non-condensable gases undergo chemical reaction, forming water molecules that are redirected for condensation. The remaining gases are subjected to cooling, radioactive decay (by containment), and adsorption processes. Then, the gases are pumped out for discharge.

Returning to the far left at the generalized function level in Fig. 6, the plant has one cooling water supply (i.e., make-up water) that directly contributes to the condensate inventory. The second cooling water supply (i.e., seawater) is pumped to facilitate heat conduction/cooling and then discharged (i.e., to the sea).

Using causal links, the generalized function level illustrates the sequence as well as the engineered processes necessary to achieve the functional purpose; this is not normally available in an AH model constructed strictly with means-ends links. The connections between processes are useful to determine those downstream processes affected by upstream disturbances. At the same time, scientific laws governing these processes can be referenced at the AFn level through the means-ends links. Similarly, causal links in the AFn level show the sequence of scientific laws exercised by the sequence of processes at the GFn. Causal links, thus, complement means-ends links, illustrating important relationships within an abstraction level that should be depicted in the displays.

4) Summary: The information content and structure for the ecological displays were built upon a WDA composed of (i) part-whole decomposition, (ii) abstraction hierarchy/structural means-ends, and (iii) causal analyses. The work domain analysis led to a psychologically relevant and physically faithful representation of the work domain that could support operators in diagnosing faults and formulating action plans in ill defined situations as required by knowledge-based tasks [11], [12]. Information identified by functional requirements analysis and the

[5]Structural connections within the PFn level are available in the PW models; however, causal relationships cannot be meaningfully applied to FP (i.e., purposes) and PFn (e.g., physical components).

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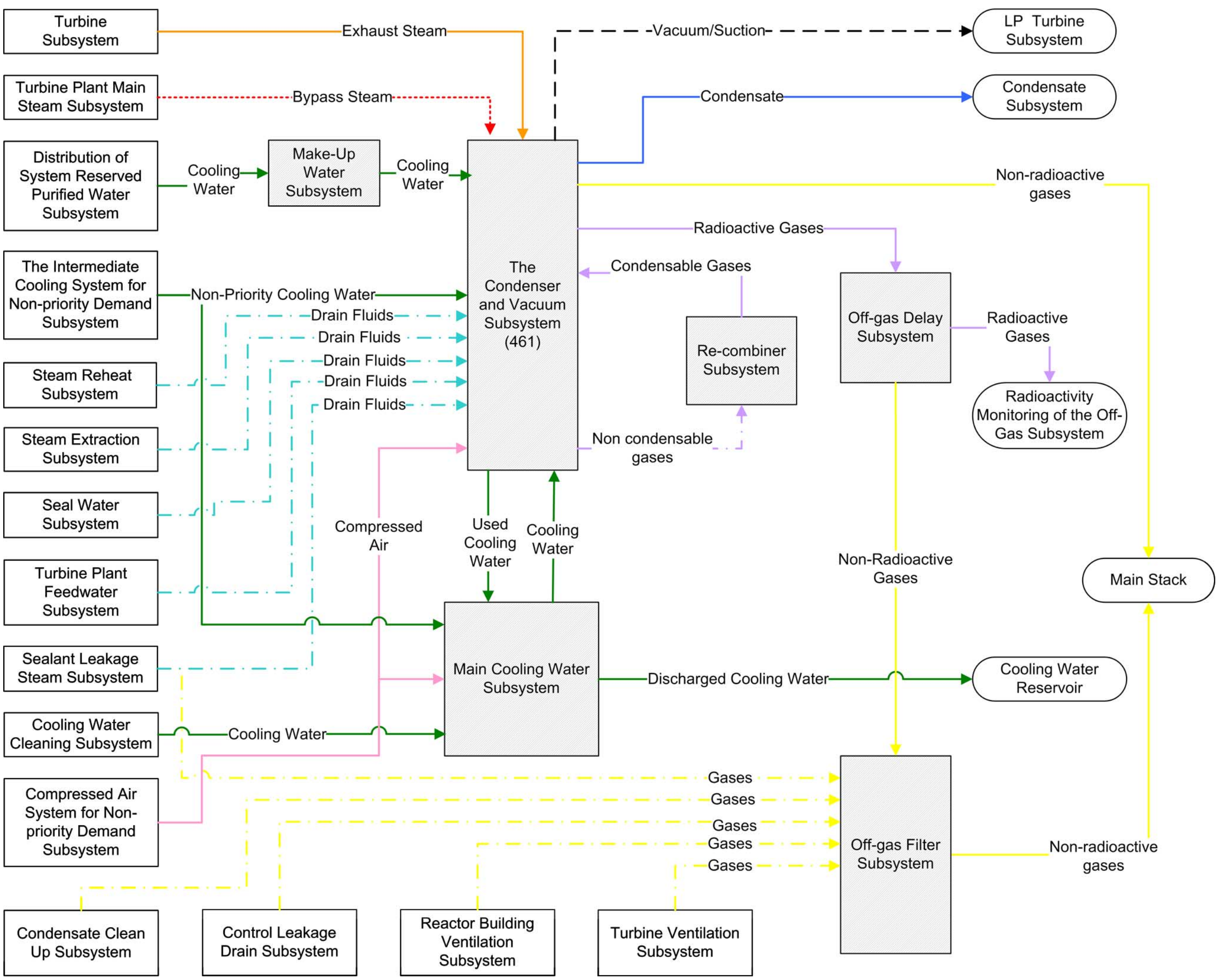

Fig. 5. Part-whole model of the condenser division at Level 2 decomposition (i.e., subsystem level). 179 × 143 mm (600 × 600 DPI).

WDA appeared to overlap. This overlap is expected as one objective of functional requirement analysis is to help engineers in reasoning about the relationships amongst high-level functions, plant systems, and operators. Given that it is psychological relevant and physically faithful, the work domain representation could also be a specification for verifying the effectiveness of the human-system interface in supporting knowledge-based tasks.

B. Ecological Displays

The WDA specifies information content and structure for an interface to support effective control of the work domain. It does not, however, specify a perceptual form for the interface. The SRK taxonomy provides guidance on transforming information content and structure into perceptual forms by assisting designers in predicting the compatibility of representational forms with human information processing.

Five ecological displays were designed for a turbine operator using Microsoft Visio™. A system programmer further translated the graphics and specifications of their dynamics into a visualization software, ProSee [53], that could communicate with the HAMBO simulator. A complete description of the entire suite of perceptual forms is beyond the scope of this article. [54]–[57] provide the full description of the displays. Hence, an overview of the entire ecological interface is presented, followed by detailed discussions of selected perceptual forms to illustrate the application of WDA and SRK as verification tool.

1) Overview: Two turbine (Figs. 7 and 8), one condenser (Fig. 9), and two feedwater (Figs. 10 and 11) displays were developed.

Turbine Displays: The two turbine displays depict process flows between the reactor and condenser in a left-to-right manner. Fig. 7 shows the first turbine display. At the top left is a trend graph of the reactor pressure, which is an indicator of steam input for the entire secondary side (Fig. 7(a)). Below the reactor pressure trend graph are the enthalpy, temperature, and pressure profiles across the entire turbine division (Fig. 7(b)). Fig. 7(c) is a valve-monitoring unit describing the behavior of control valves on the mimic diagram below. At the bottom right is a mimic diagram depicting steam flow discharged from the reactor to the high-pressure turbine (Fig. 7(d)). Mass balances are integrated in the mimic diagram to detect coolant/steam losses.

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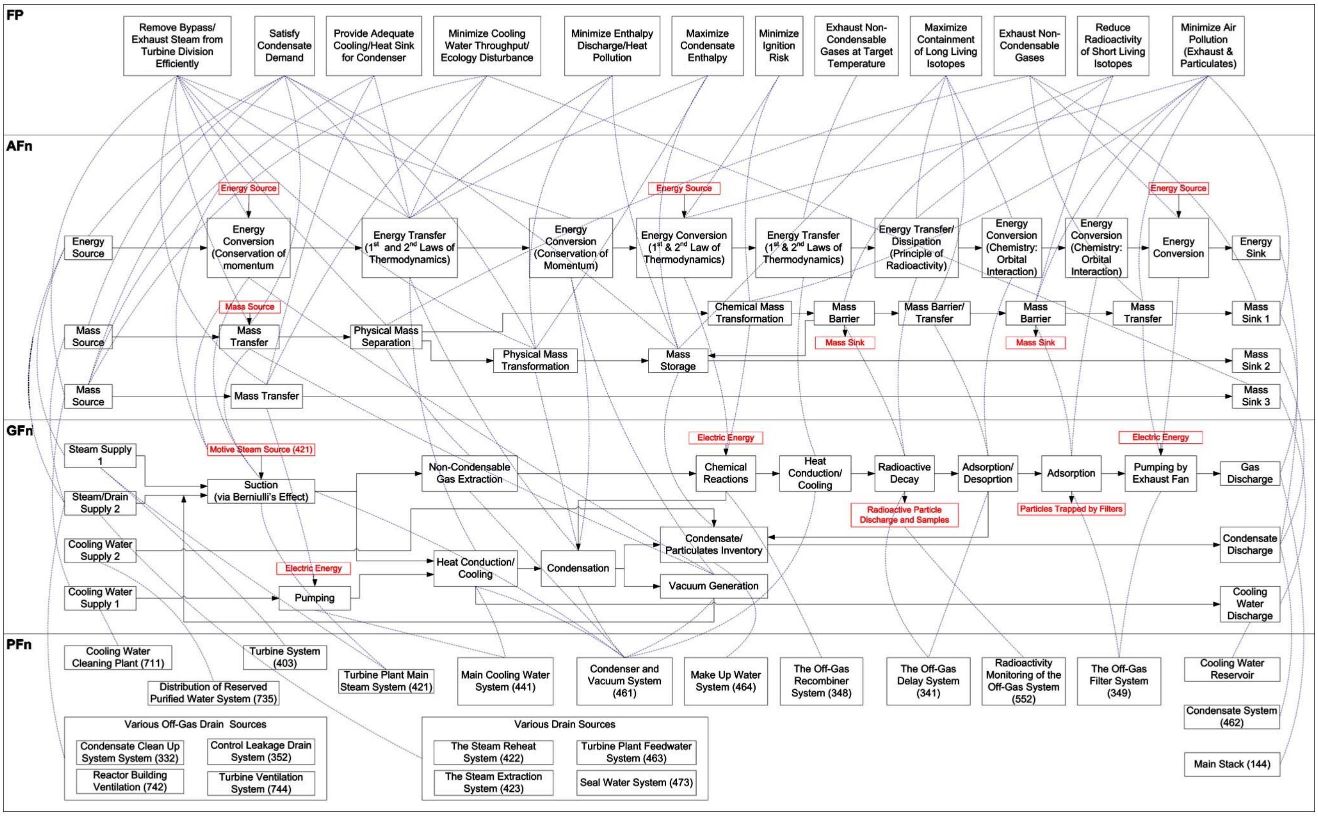

Fig. 6. AH model of the condenser division at Level 2 decomposition (i.e., subsystem level). 179 × 292 mm (600 × 600 DPI).

Fig. 8 shows the second ecological display for the turbine division. The top left of this display shows another valve monitoring unit for the control valves (Fig. 8(a)) in the mimic diagram (Fig. 8(c)) appearing below. To the right of the valve monitoring unit are trend graphs of major storage tanks (Fig. 8(b)). The bottom half of this display presents a mimic diagram integrated with mass balances, depicting process flows from the high-pressure to the low-pressure turbines (Fig. 8(c)). The bar graph at the far left (which replicates the one at far right of Fig. 7(d) shows steam exhaust from the high-pressure turbine, while the graph at the far right shows steam output to the condenser and feedwater divisions. The exhausts of the low-pressure turbines are dumped into the condensers for latent heat extraction as illustrated by the downward arrows from the three turbine icons to the three-chamber condenser icon in Fig. 8(c).

Condenser Display: The ecological interface for the condenser division (Fig. 9) depicts the operation of the condenser and its supporting subsystems. At the top left are start-up ejector components for reducing pressure during plant start-up (Fig. 9(a)). Directly below is the three-chamber condenser icon embedded with level and pressure trend graphs (Fig. 9(b)). To the left of the condenser icon are the regular ejector components with two identical valve monitoring units (Fig. 9(c)). At the top right are two tanks embedded with pressure-temperature plots to illustrate the re-combination process (Fig. 9(d)). The bottom right depicts a seawater monitoring unit showing the changing properties of seawater across the condenser as well as the operating conditions of the seawater pumps (Fig. 9(e)). To the left of the seawater monitoring unit is an energy balance, representing the instantaneous relationship between energy gain to the seawater and energy loss from the steam (Fig. 9(f)). The energy loss from the steam is connected to the condenser efficiency monitoring unit containing mass balance, energy balance, and pressure-temperature plot of the condenser at the bottom left (Fig. 9(g)). Beside the pressure-temperature plot are arrows pointing to three condensate pumps, which draw condensate from the condenser hotwell for the feedwater division.

Feedwater Displays: The two feedwater displays depict the pressurizing and pre-heating processes between the hotwell and the reactor. Both feedwater displays orient the process flow from right to left. Fig. 10 is the first feedwater display. The middle region consists of a mimic diagram illustrating the process flow from the condenser icon to the feedwater tank icon (Fig. 10(c)). The top right presents a plot describing the condensate pump operations in drawing condensate from the condenser hotwell (Fig. 10(a)). The plot of the condensate pumps connects to the mass balance, which depicts the mass entering and leaving the components inside the control volume. The control volume is the area of the mimic diagram that is light grey in colour. To the left of the mass balance is a valve monitoring unit (Fig. 10(b)). The bottom region below the mimic diagram is a temperature profile that illustrates heat exchanges of condensate with bleed steam (Fig. 10(d)).

Fig. 11 shows the second ecological display of the feedwater division. The mid-horizontal region, Fig. 11(c), contains a mimic diagram showing the components from the feedwater tank to the reactor. Similar to Fig. 10, the top region shows

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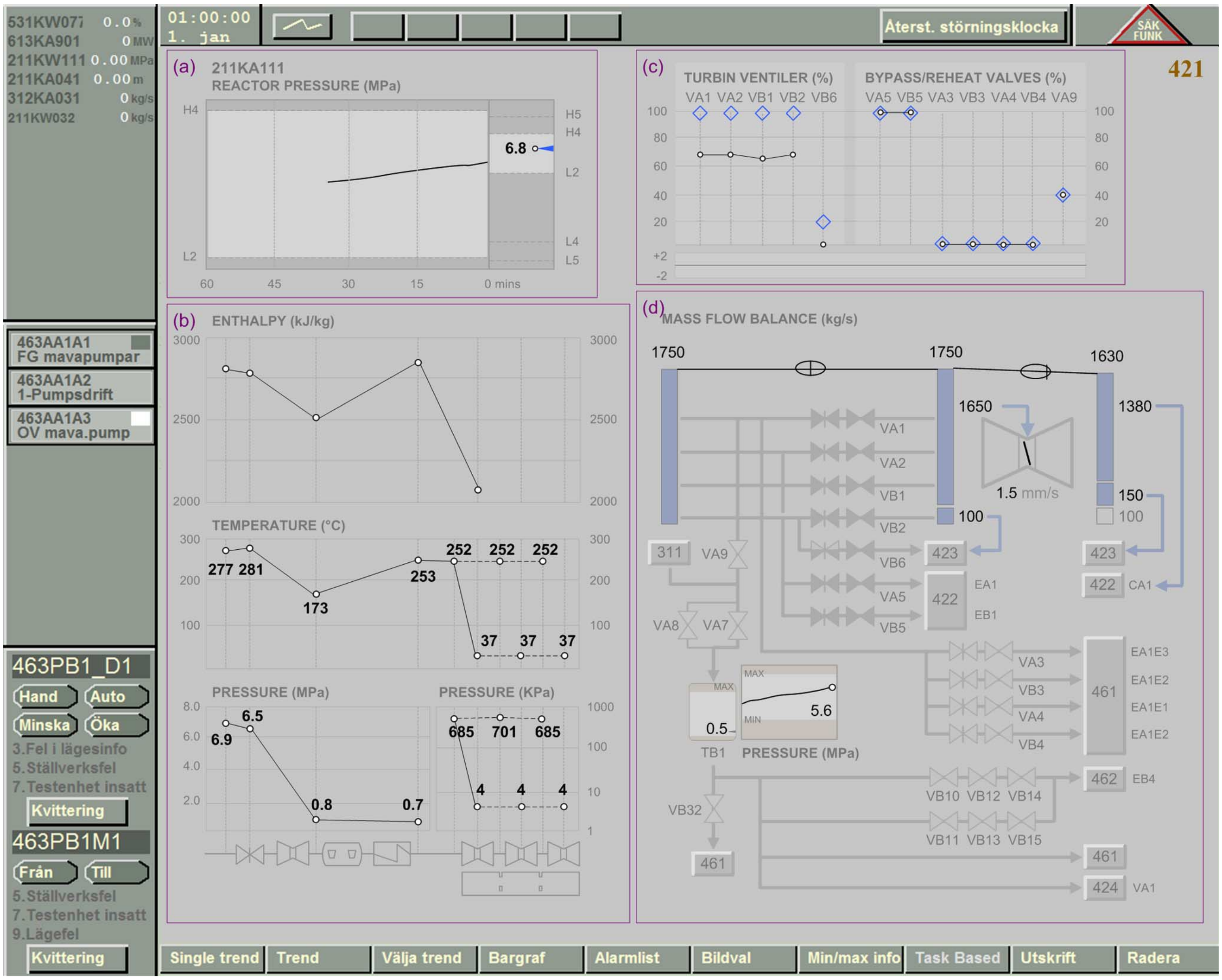

Fig. 7. The first ecological display for the turbine division. (a) Reactor pressure trend graph. (b) Enthalpy, temperature, and pressure profiles of the turbine division. (c) Valve monitoring unit. (d) Mimic diagram integrated with mass balance depicting process flow from the reactor to the high-pressure turbine. 179 × 143 mm (300 × 300 DPI).

feedwater pump graphs, a mass balance for the control volume (Fig. 11(a)), and a valve monitoring unit (Fig. 11(b)). The bottom-horizontal region shows another temperature profile illustrating heat exchange processes of feedwater (Fig. 11(d)). Fig. 11(e) depicts part of the reactor containing valves and a reactor water level trend graph.

This overview of the ecological displays (Figs. 7–11) presents the basic appearance of the design. However, a more detailed discussion of selected graphical forms is necessary to demonstrate how the WDA and SRK taxonomy contribute to the design and verification of these displays.

2) Design and Verification of Selected Graphical Forms: In this subsection, we discuss three graphical forms in detail to substantiate the claim that application of EID can contribute to design and verification of displays which support monitoring and diagnosis, particularly within knowledge-based tasks. First, we present relevant portions of the WDA that serve as a basis for design and verification of each graphical form. Then, we describe each graphical form to verify that the information identified by the WDA is represented. We also illustrate the anticipated benefits of each graphical form for monitoring and diagnosis to verify that the graphical form represents information content and structure in a manner compatible to human information processing. These detailed descriptions serve as an example of verifying displays with respects to criteria derived from both the WDA and the SRK taxonomy.

Condenser Efficiency Monitoring: Fig. 9(e) presents the graphical form for monitoring condenser operations[6]. The pertinent domain information for this form was discovered in the AH model of the condenser subsystem (Level 3 part-whole decomposition). Fig. 12 is a simplified AH summarizing the pertinent information.

Two relevant functional purposes are to satisfy condensate demand of the feedwater division and to maximize efficiency of the low-pressure turbine. The means to achieve these purposes are through application of the laws of conservation of mass, energy, and momentum at the abstract function level. In creating energy differentials inside the condenser, condensate can be converted

[6]This design is an adaptation of an EID interface found in DUal Reservoir System Simulation (DURESS) [40].

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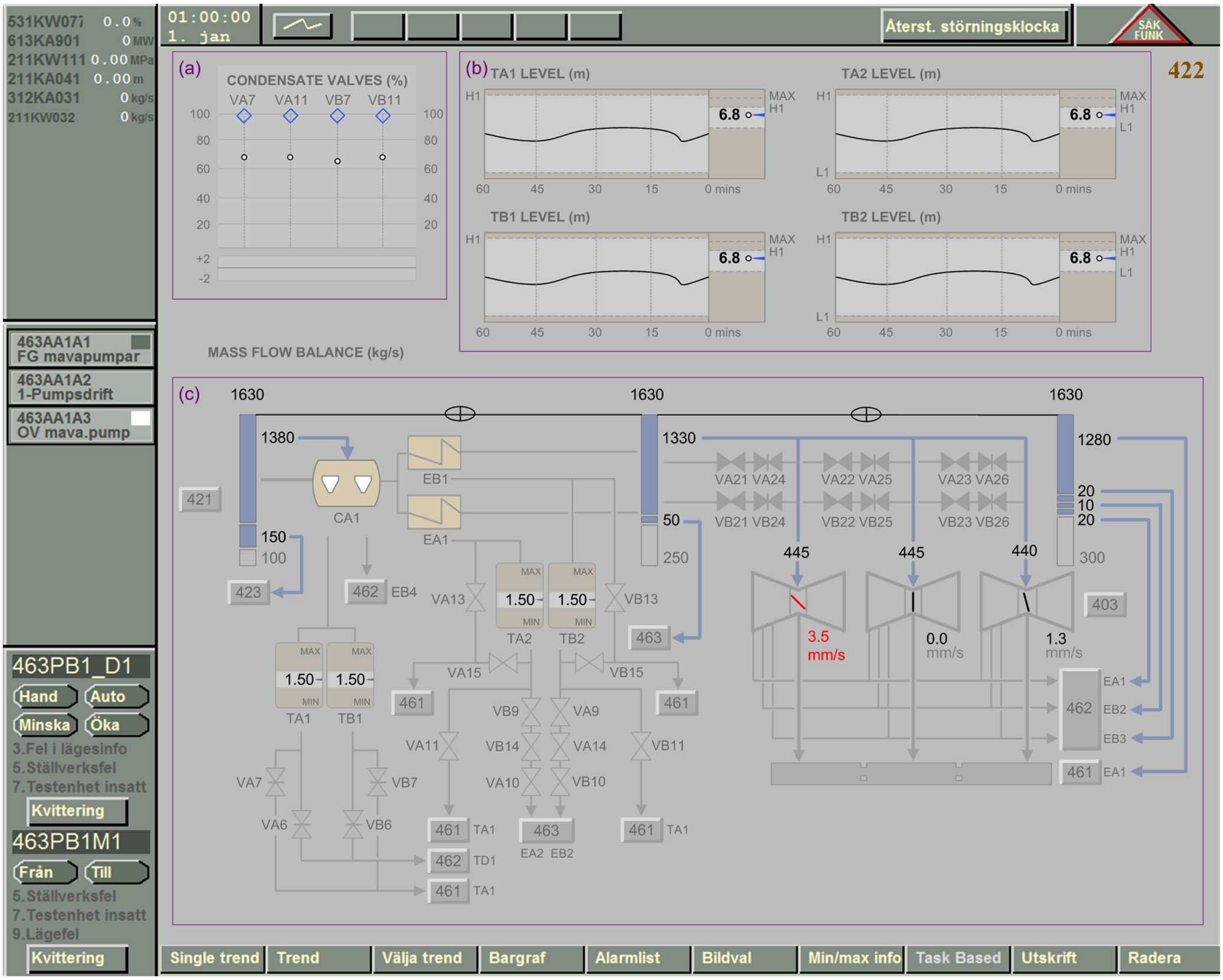

Fig. 8. The second ecological display for the turbine division. (a) Valve monitoring unit. (b) Level trend graphs for major tanks. (c) Mimic diagram integrated with mass balances depicting process flow from the discharge point of the high-pressure turbine to discharge points of the low-pressure turbines. 179 × 143 mm (300 × 300 DPI).

through heat transfers. In maximizing the momentum differential across the low-pressure turbines, the operating efficiency of the turbines is optimized.

The laws at the abstraction function level can be achieved by processes at the generalized function level. The heat conduction/latent heat removal process can lead to condensation, creating a vacuum for the turbine division and providing condensate for the feedwater division. Studying the processes of condensation and vacuum generation in the WDA led to the identification of the saturation curve of water as a domain constraint for the relationship between pressure inside the condenser and temperature of the condensate.

At the physical function level, the equipment used to perform these processes includes the condensers, seawater pumps, and ejectors. For the purpose of this example, detailed discussions on the seawater monitoring (Fig. 9(g)) and ejectors monitoring (Fig. 9(c)) units are omitted (see [56], [57] for details).

We now show how the interface conveys these portions of the AH through a mass balance, energy balance, and pressure-temperature plot. First, the mass and energy balances illustrate the functional purpose and abstract function information (Fig. 13).

The mass balance indicates how well the condenser is satisfying the condensate demand of the feedwater division. The inlet and outlet are represented by the two horizontal bar graphs at the top and bottom, respectively. The two bar graphs are also connected with a line to illustrate their difference. The vertical bar graph in the center represents a mass reservoir in the hotewell. Under steady-state conditions, the mass inlet and outlet should be equal, resulting in a vertical connecting line and a stable mass reservoir. The mass inlet also serves as an indicator of condenser efficiency. At a given power level, a lower mass input (i.e., steam exhaust) suggests a higher efficiency (e.g., low pressure inside the condenser).

The energy balance illustrates the operating capacity of the condenser by accounting for both mass and temperature. At steady state, the energy inlet and outlet should also be equal, leaving the energy reservoir in the hotwell constant. Similarly, at a given power level, a lower energy input suggests higher efficiency operation.

The AH in Fig. 12 identifies three processes at the generalized function level as means to the abstract functions. The first process is heat conduction, which is depicted by the seawater

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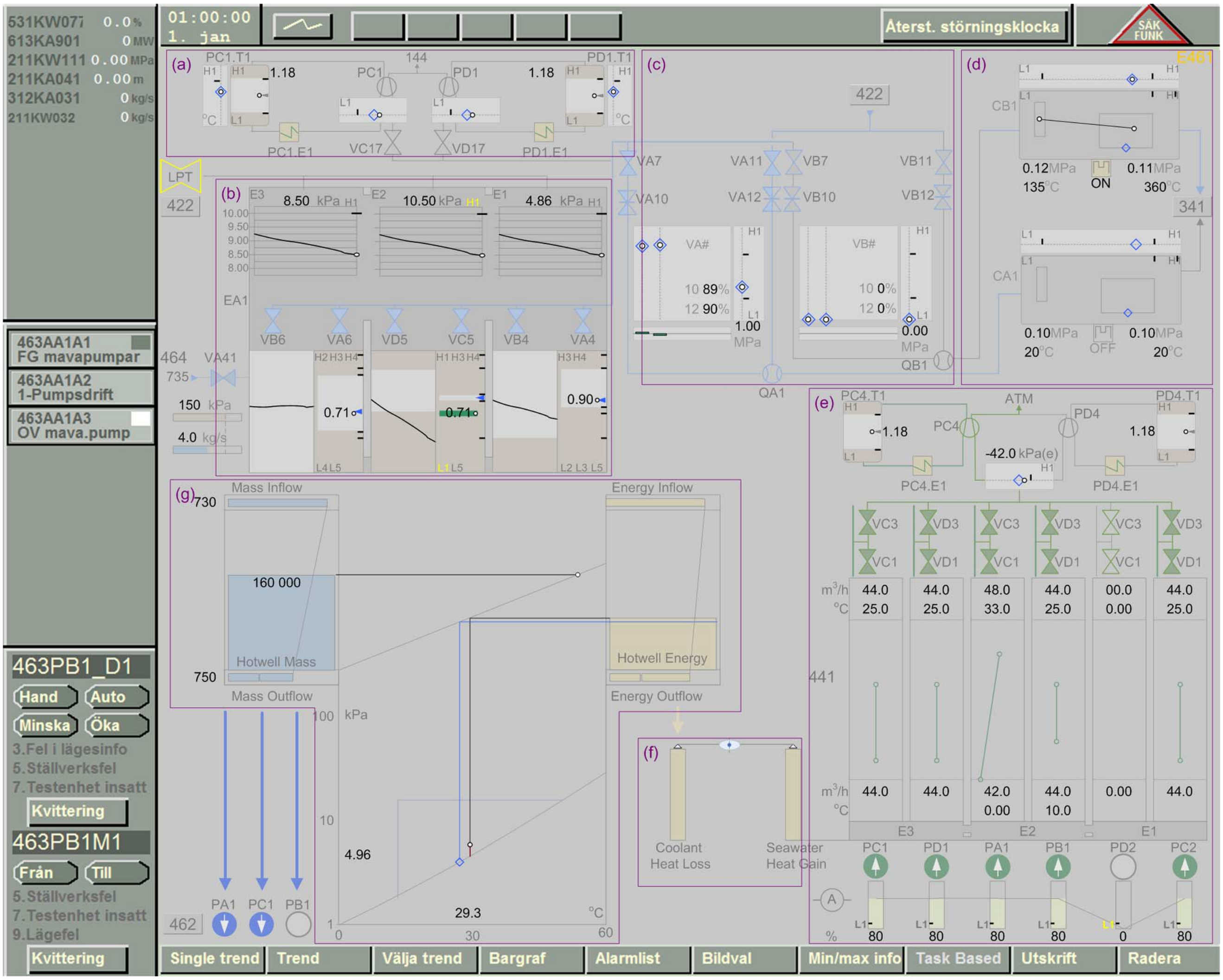

Fig. 9. The ecological display for the condenser division. (a) Start-up ejector units. (b) Three-chamber condenser embedded with pressure and level trend graphs. (c) Regular ejector units with valve monitoring units. (d) Re-combiners embedded with temperature-pressure plots. (e) Seawater monitoring unit. (f) Energy balance depicting heat loss by coolant and heat gained to seawater. (g) Condenser efficiency monitoring unit composed of a mass balance, energy balance, and temperature-pressure plot. 179 × 143 mm (300 × 300 DPI).

monitoring unit in Fig. 9(e). The relevant information about the heat conduction process at the generalized function is linked to the abstract function through another energy balance (Fig. 9(f); see [56]–[58] for details).

The second and third processes are condensation and vacuum generation, which occur inside the condenser. The temperature of the condensate in the condenser hotwell and the pressure inside the condenser are mapped onto a plot that depicts the condensation and vacuum generation processes (Fig. 14). The circle and blue diamond indicate actual and expected values at a given power output level, respectively. The diagonal grey line spanning across the graph represents the pressure-temperature saturation curve of water, which is identified as a domain constraint. The blue vertical and horizontal lines connecting to the saturation curve mark the allowable operating region under steady-state conditions. The condensation process is also partially depicted by the mass balance. The relationships between the abstract function and generalized function levels can be inferred through projection lines from the circle and blue diamond to the energy balance. For a complete account of the geometric relationships amongst the variables, see [40].

This detailed description is, in effect, a process of verifying that the information content and structure specified by the work domain analysis are mapped onto a graphical form in the ecological interface. The identified domain information, such as mass input-output balance and pressure-temperature constraints, is theoretically necessary to detect faults and assess efficiency. In other words, this graphical form externalizes parts of a psychologically relevant and physically faithful model of the work domain to support operators in problem solving.

In addition to information content and structure, we further verify that this graphical form permits operators to rely on lower levels of cognitive controls, a design principle derived from the SRK taxonomy to improve human-interface compatibility. The balances (Fig. 13) depict input-output equilibrium by a connecting line, which is a form of signal or sign (i.e., time-space indicators or familiar percepts) that can trigger SBB or RBB as opposed to symbols (e.g., numbers) that activate KBB (e.g., nu-

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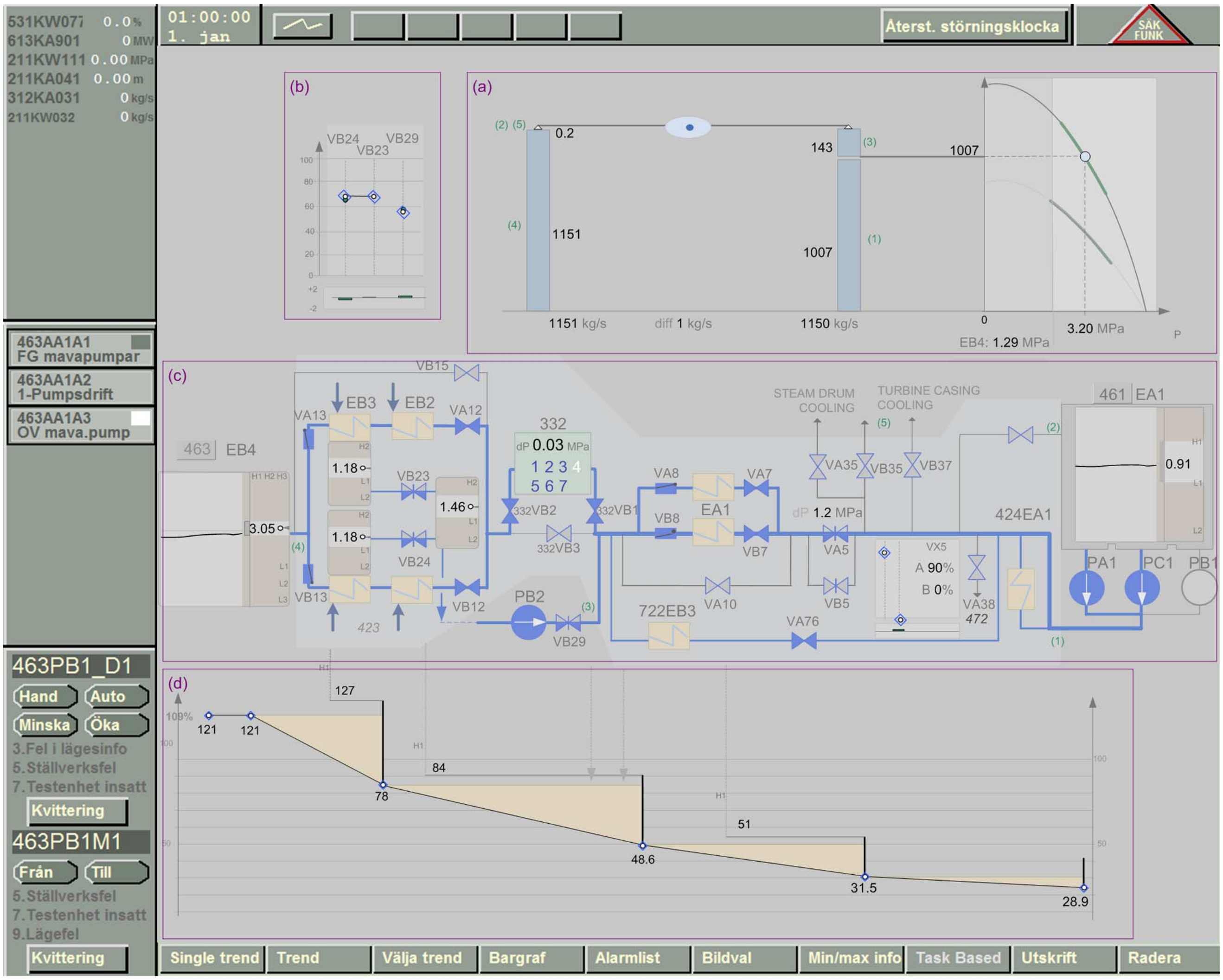

Fig. 10. The first ecological display for the feedwater division. (a) Condensate pump monitoring unit and mass balance. (b) Valve monitoring unit. (c) Mimic diagram depicting process flow from the condenser hotwell to the feedwater tank. (d) Temperature profile depicting heat exchanges in the mimic diagram. 179 × 143 mm (300 × 300 DPI).

merical computations). The changing angles of the connecting line form time-space signals or signs that perceptually communicate the rate of change for the reservoirs, with a vertical line illustrating zero rate of change. The energy balance also provides an unambiguous indication of system stability of the condensation process in thermodynamic terms. This relieves operators from mental calculation using temperature and mass data for knowledge-based tasks.

The temperature-pressure plot of the condenser capitalizes on similar human perceptual capabilities. The horizontal and vertical displacement from the circle to the blue diamond indicates the magnitude of heat exchange and non-condensable gas extraction inefficiencies, respectively. Furthermore, the plot (Fig. 14) is separated into three regions: Normal (inside steady state operating region); Abnormal (outside steady state operating region and above the saturation curve); and, Emergency (below the saturation curve). The motion and location of the operating points (i.e., white circle) in the context of the inherent system constraints depict system states in the forms of signals and signs, permitting operators to monitor condenser's performance perceptually.

The balances and temperature-pressure plot, which communicate the information identified in the abstract and generalized functions, respectively, share some means-ends relationships. These relationships are depicted by the projection lines from data points on the plot (i.e., circle and blue diamond) to the energy balance that can support operators in monitoring tasks (Fig. 15). These projection lines visually translate deviation of heat exchange efficiency in terms of temperature into energy. As mentioned, energy is a useful indicator because it accounts for both mass and temperature. Large energy deviations can be alarming as stable shifts between energy states are usually slow. The projection lines also facilitate pattern recognition or rule-based behaviors. As the mass, energy, temperature, and pressure deviate from steady-state conditions, the projection lines form a distinctly different visual pattern, which is in the form of either a signal or sign to facilitate information processing of potential process disturbance (Fig. 16).

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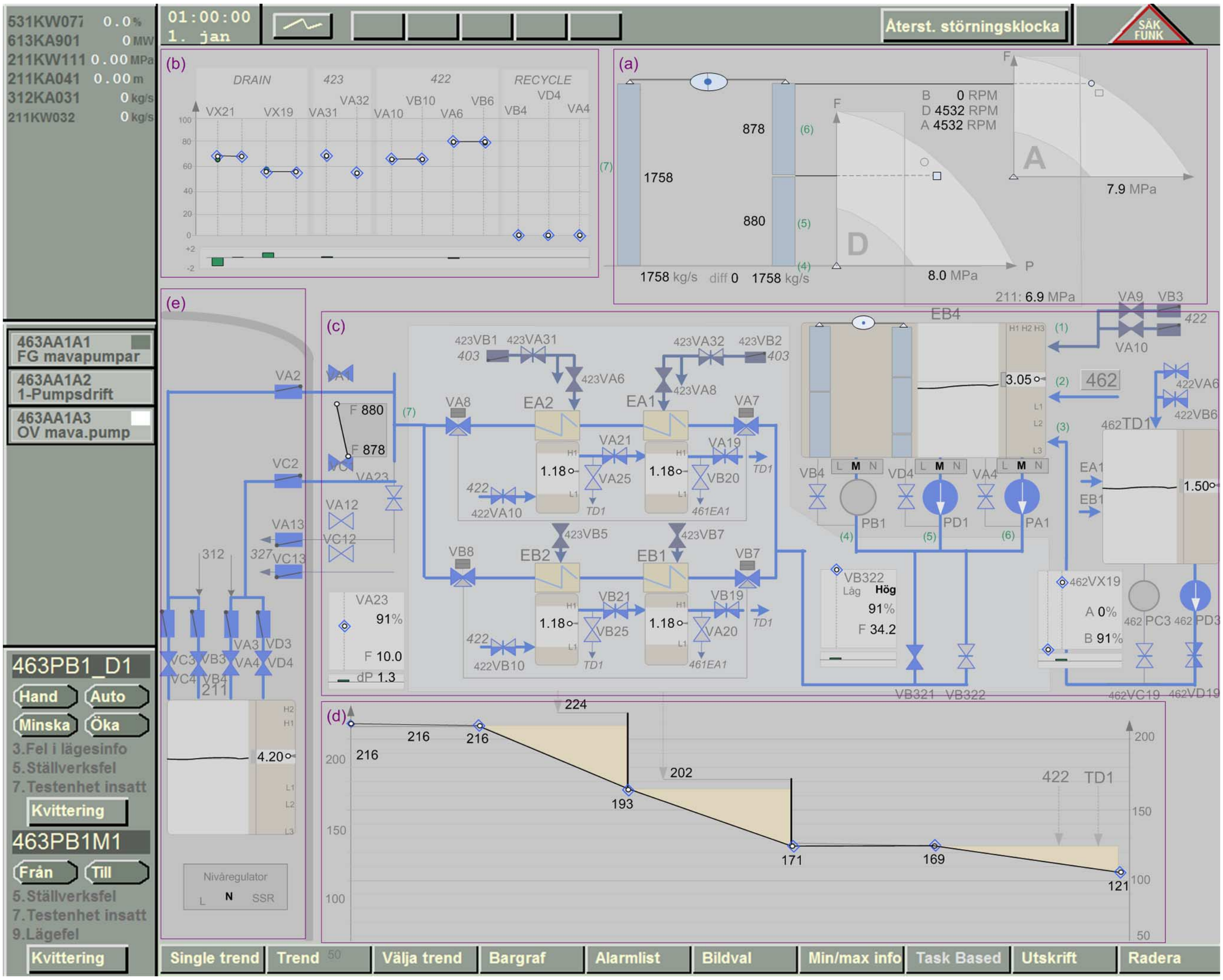

Fig. 11. The second ecological display for the feedwater division. (a) Feedwater pump monitoring units and mass balance. (b) Valve monitoring unit. (c) Mimic diagram depicting process flow from the feedwater tank to the reactor. (c) Reactor tank embedded with equipments and a level trend graph. (d) Temperature profile depicting heat exchanges in the mimic diagram. 179 × 143 mm (300 × 300 DPI).

Condensate Supply Monitoring: Fig. 10(a) presents the graphical form for monitoring the condensate pump operations. The information requirements are defined based on the AH of the condensate subsystem (Level 3 part-whole decomposition) in the feedwater division. The functional purposes are to satisfy condensate demand of the feedwater tank and to maintain target feedwater tank pressure, both of which are achieved by means of mass transport according to conservation of mass at the abstract function level.

Mass transport is achieved by means of pumping at the generalized function level. One constraint identified in the WDA is that mass transports can only be established by pumping the condensate at a discharge pressure higher than the pressure of the receiving tank. One or two of the three condensate pumps and a common recycle valve (which appeared at the physical function level) regulate the pumping process. The condensate pumps are fixed-speed centrifugal pumps, which have an operating capacity constrained by a set of pump curves that specify the range of pressures and flow rates. If the condensate pressure is higher than the pre-defined limit, the recycle valve returns the fluid to the condenser, and in effect, reduces the efficiency of the condensate subsystem.

A mass balance and a pressure-flow rate plot (Fig. 10(a)) depict the identified work domain information. The mass balance (Fig. 17 or the left part of Fig. 10(a) illustrates the functional purpose and abstract function in terms of satisfying condensate demand of the feedwater tank and adhering to the law of conservation of mass. The left and right vertical bar graphs are the total mass leaving and entering the control volume (which is the area colored in the lightest grey in Fig. 10(c), respectively. These are also summation bar graphs that show distribution of input from different sources and output to different sinks. When the two bar graphs are the same, the line connecting them should be horizontal and the center of the bubble/oval should be aligned to the center of the connecting line. When the mass balance constraint is violated across the control volume, the line rotates and the bubble slides along the line towards the bar graph of greater value, similar to a bubble in a spirit level. The displacement of the bubble is scaled to be sensitive to small deviations between the bar graphs. The structural means-ends relationship between

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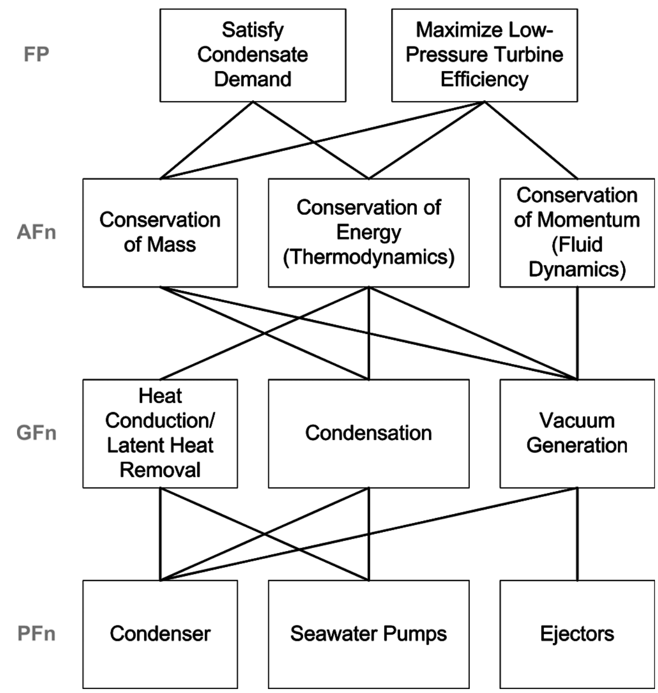

Fig. 12. Simplified, distilled level 3 AH for condenser subsystem in the condenser division. 87 × 93 mm (600 × 600 DPI).

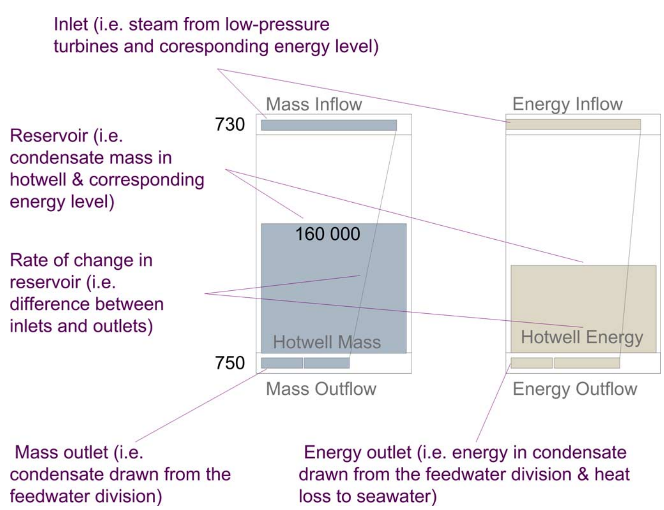

Fig. 13. Mass and energy balances depicting the FP and AFn of the condenser. 88 × 71 mm (600 × 600 DPI).

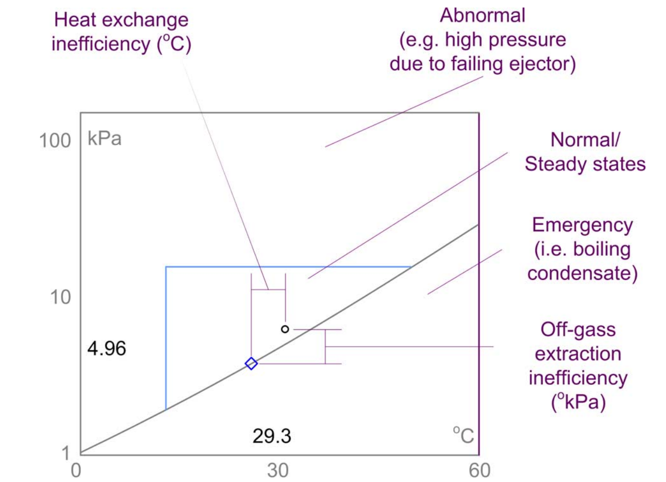

Fig. 14. Temperature-pressure graph of the condenser. 88 × 66 mm (600 × 600 DPI).

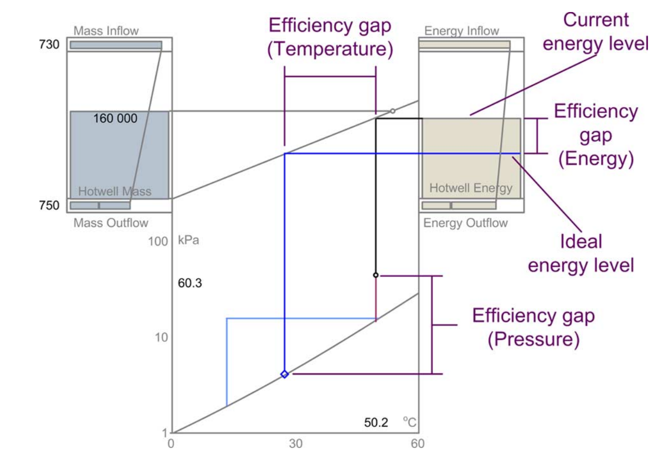

Fig. 15. Integrated graphical forms depicting efficiency gaps of the condenser. 88 × 65 mm (600 × 600 DPI).

first principles and the ensuing process is illustrated by a line connecting the bar graph at right to the pressure and mass flow operating point (i.e., white circle) on the pressure-flow rate plot (Fig. 18, or the right part of Fig. 10(a).

The pressure-flow rate plot depicts the operation of the condensate pumps in the mimic diagram (Fig. 10(c)). The mass balance and pressure-flow rate plot share a common vertical axis of mass flow rate, enabling this line to represent the mass input by the condensate pumps in connection to their operating parameters (i.e., flow rate and pressure). Two work domain constraints are embedded in this pressure-flow rate plot. First, a vertical line marks the feedwater tank pressure—the minimum that the condensate pumps must overcome to establish mass transport. Second, the operating points of the condensate pumps are restricted by the two pump curves. The upper and lower pump curves describe two-pump and one-pump operating modes, respectively. Under normal operating conditions, the operating point may only move along one of these curves, with the active one being highlighted.

The detailed description verifies that the graphical form embeds information specified by the work domain analysis to be necessary for monitoring under all situations. Furthermore, this graphical form is verified to convey relevant information in such a way that promotes skill- and rule-based behavior. It is also shown to support knowledge-base behavior by mapping relations between operating parameters of the components, purposes of the subsystem, and domain invariants.

The establishment of mass transport to achieve the primary objective of supplying condensate is demonstrated with the mass balance. The summation bar graphs are designed to communicate inefficiencies. In the case of substantial recycling of condensate, the portion of the bar graph at left, designated to recycle condensate mass output to the condenser, would become increasingly visible or even dominating suggesting an inefficiency typically caused by low total flow rates. On the other hand, faults violating mass conservation, such as leakage

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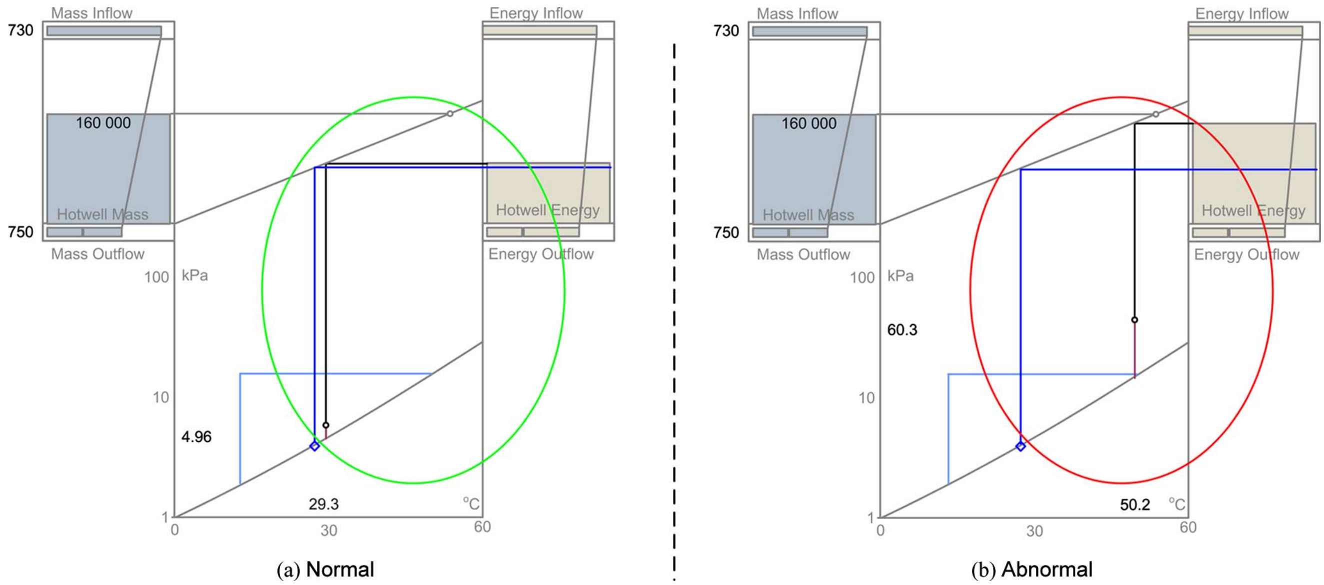

Fig. 16. Integrated graphical forms facilitating pattern recognition for monitoring. (a) Normal conditions. (b) Abnormal conditions. 179 × 81 mm (600 × 600 DPI).

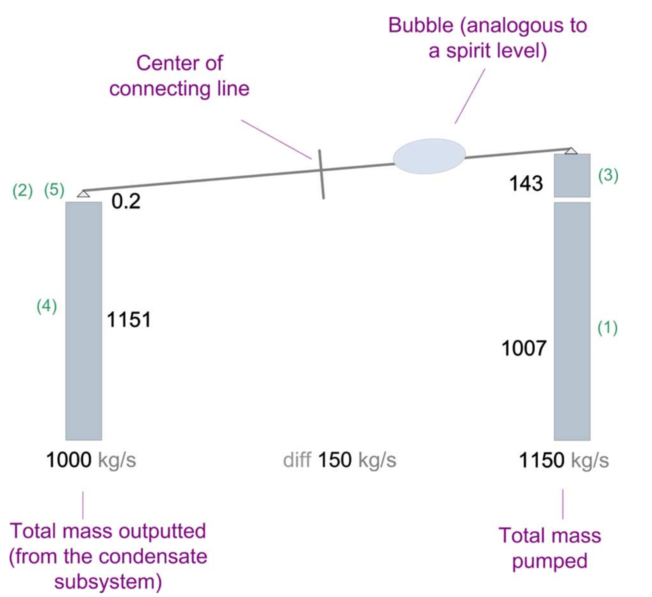

Fig. 17. Mass balance of the graphical form for monitoring condensate subsystem. 88 × 85 mm (600 × 600 DPI).

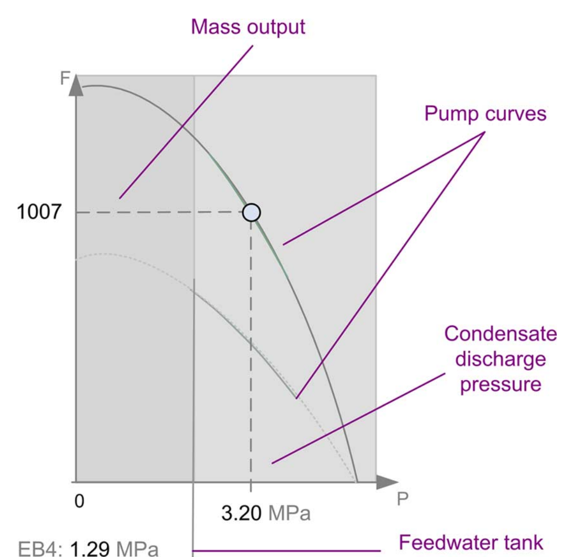

Fig. 18. Pressure-flow rate plot for monitoring condensate subsystem. 83 × 85 mm (600 × 600 DPI).

within the control volumes, are communicated through the line rotation and bubble location of the mass balance (Fig. 17). The pressure-flow rate plot illustrates operating constraints. The constraint of minimum discharge pressure for the pumps to deliver condensate can be detected by locating the operating point (white circle) with respect to the vertical line that depicts the feedwater tank pressure. In other words, an operating point located to the left of this vertical line (darker area of the plot) means that condensate is not being transported to the feedwater tank. Operating points deviating from the pump curves indicate equipment malfunctions. The intersection between each pump curve and the vertical line of the feedwater tank pressure defines the maximum flow capacity (an operating limit) for each operating mode. This graphical form captures information content and structure with minimal use of symbols (i.e., numbers) allowing the operators to rely on lower levels of cognitive control for monitoring and diagnosis.

Valve Panel: The graphical form for monitoring valve operations was first designed for the feedwater subsystem in the feedwater division and later adopted in the other ecological displays (e.g., Fig. 11(b)). In contrast to other graphical forms of the ecological displays, the valve monitoring unit design is largely based on information contained in the Level 4 part-whole model, although the design was also guided by AH models of feedwater subsystem Level 3 part-whole decomposition. As mentioned, the analysts found that WDA at Level 3 decomposition (stopping at units of components) was useful for understanding the purpose, first principles, and

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processes of the feedwater subsystems, but not sufficiently detailed to capture the inter-component relationships necessary for operators to optimize control of the bleed steams[7]. Thus, a Level 4 part-whole analysis was conducted.

Key elements discovered at this level were: 1) equally distributed bleed steam across heat exchangers results in higher efficiency, in accordance with the laws of thermodynamics; 2) valve positions provide a basis to infer relative flow rates; and 3) valve positions are set by the control system in the turbine division. The expected positions under steady-state conditions for automatically controlled valves are known for each power level, thus providing references for detecting deviations.

Fig. 11(b) portrays the information content discovered in the Level 4 part-whole model. The position of each automatically controlled valve is depicted by a small circle along a vertical axis that indicates percentage of opening. Each blue diamond represents the expected valve position for a given power level. All circles should be ideally located inside their respective blue diamonds. Valves belonging to parallel flows are placed beside one another and connected with lines. These lines are perfectly horizontal under normal conditions (i.e., equally distributed flows and properly functioning valves). The lower part of the graphical form contains green bar graphs representing the difference between controller output and actual valve position. The bar graphs are invisible during fault-free operation. The description of these features verifies that this graphical form contains the information specified by the work domain analysis necessary to support knowledge-based tasks.

The graphical form for monitoring valve behaviors is again intended to support the operator at all three levels of cognitive control, adhering to the EID principle derived from the SRK taxonomy. In terms of KBB, this form illustrates the relationships between valves, simplifying comparisons between positions of different valves. The horizontal lines connecting valves in parallel and the blue diamonds depicting expected values permit operators to rely on SBB or RBB for detecting anomalies. Similarly, the green bar graphs provide visually salient indications of discrepancies between set points and actual values, which usually indicate fault conditions such as stuck valves.

3) Summary: Five ecological displays were designed to represent the information content and structure identified by the WDA. These displays contain graphical forms that permit operators to rely on lower level of cognitive control, an EID principle derived from the SRK taxonomy to improve interface compatibility with human information processing. To illustrate the viability of EID for improving verification, we described three graphical forms in detail to verify that information identified by the WDA (i.e., criteria for information content and structure) can be fully represented; and demonstrate the anticipated benefits for monitoring in terms of the SRK taxonomy (i.e., criteria for forms based on human perceptual capabilities) to verify that the displays are compatible with human information processing. This process indicates that EID is not only effective as a design tool but also as a verification tool that helps to ensure interface compatibility with operators.

[7]The deign decisions here were also influenced by the lack of sensors for measurement or derivation of flow rates in the feedwater subsystem. This design could therefore only be based on valve position data. Sensor availability in the context of EID is included as a topic for future work.

IV. Discussion

We have illustrated that the EID framework can serve as both a design and verification tool to develop and evaluate displays for the secondary side of a BWR. To put this work in context with current research and practice, this section discusses the unique contributions of this study, its limitations, and prospects for future work.

A. Unique Contributions

This research offers several contributions. The EID products described here are unique to the open literature, providing the first detailed account of ecological displays for a simulator of an operating nuclear power plant. The detailed descriptions of selected graphical forms demonstrate anticipated benefits in supporting monitoring and diagnosis. In sum, this proof-of-concept expands on the foundation of prior research, confirming that the EID framework can be meaningfully scaled up to meet challenges faced by the nuclear industry (see [46]–[49], [52]).

The descriptions of the EID products serve as a detailed, representative example to assist NPP interface designers in putting the framework into practice. First, we have demonstrated that the WDA can specify information content and structure to support problem solving, especially during unanticipated events that are often precursors of major accidents (see [25]–[27]). The AH helps designers to conceptualize work domains in a psychologically relevant manner as opposed to relying on physical and process perspectives that do not explicitly support knowledge-based, ill-defined tasks. Second, based on the SRK taxonomy, we have demonstrated the anticipated benefits of the ecological displays by representing information compatible with human information processing. The taxonomy assists designers in predicting information processing performance of visual forms, thereby informing effectiveness of designs in capitalizing on innate human perceptual capabilities.

EID is also presented as a tool that could improve verification or analytical evaluation as proposed in [39]. Through the WDA, we specify verification requirements on information content and structure that explicitly aim to support problem solving, especially during unanticipated events. These requirements complement those generated by task analyses (or task support verification). As a potential framework for functional requirement analysis, the WDA information requirements ensure that the interface captures the necessary functional information (i.e., system objectives, system functions, and system-function relationships) for monitoring and diagnosis. The EID framework also specifies that the interface should not force operators to engage at levels of cognitive control higher than necessary. We evaluate the conformance to this specification or principle by verifying that information is primarily represented in the forms of signals and signs supplemented with symbols, thereby ensuring the maximum interface compatibility with human information processing.

The ecological displays have been implemented in a high-fidelity simulator, have undergone functional testing by process

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experts, and have served as a test bed for empirical research (see [35]). This work therefore takes the first step toward a series of validation studies to determine the practical benefits that EID could bring to the nuclear domain.

B. Limitations

The highly representative nature of this design case study comes with several limitations. First, our scope was limited to the secondary side of the plant because we have greater access to turbine operators than reactor operators to serve as participants in upcoming empirical evaluation/validation studies. Our choice of analysis scope was also influenced by the fact that the secondary side was readily decomposed into three sections for allocation to the three design teams. Developing ecological displays for the primary side remains an outstanding research goal. The primary side introduces engineering complexities and threats to safety that exceed those encountered in secondary systems, providing a challenge for further verification research on EID in the nuclear domain.

Although implementation of this interface includes user interaction, we excluded the design of innovative control features to reduce training demands on the operators for the empirical study as described in a companion article [35]. Thus, the potential benefits of coupling control at the component level to higher-order properties such as energy have not yet been examined. The design of control features that satisfy the EID principles demands additional work.

C. Future Work

Future studies are necessary to address other viability issues associated with the EID framework that were not explored as part of this study. Technical requirements such as additional sensors to satisfy information demands remain to be addressed (see [59], [60]). These requirements have direct implication on cost and, thus, viability of EID application. More generally, research on cost-benefit trade-offs related to interface development and implementation is also necessary to assess the viability of this framework. Finally, a more detailed account of the process of applying EID at an industrial scale would be an invaluable complement to the product description provided here.

V. Conclusion

The objective of this research program is to investigate the potential benefits that EID could bring to the nuclear industry. This article presents evidence that EID could improve interface design and verification practice in the nuclear industry. In applying the framework to the secondary side of an operating BWR plant, we have shown that EID is effective in addressing interface design challenges on a practical scale. In the descriptions of EID products, we have illustrated two concepts: 1) how a WDA reveals relevant domain characteristics that are theoretically necessary to support effective monitoring and diagnosis, and 2) how the SRK taxonomy assists the designer in predicting how information processing performance will be facilitated by visual representations of the domain information content and structure. We also illustrate that the EID framework could enhance current verification practice through the conduct of a WDA that specifies the functional information that should be contained in the interface to support problem solving. These findings contribute to the growing support in the academic literature for work domain-based interface design approaches. While demonstration or verification is illustrative of design features, interface effectiveness must be confirmed through validation. In a companion article [35], we present the first empirical evaluation of these ecological displays with professional operators, thereby, initiating the process of validating EID in the nuclear domain.

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References

[1] F. L. Toth and H. Rogner, "Oil and nuclear power: Past, present, and future," *Energy Economics*, vol. 28, pp. 1–12, 2006.
[2] R. K. Lester, "New nukes," *Issues in Science and Technology*, vol. 222, pp. 39–46, Summer 2006.
[3] World Nuclear Assoc., WNA Report: The New Economics of Nuclear Power World Nuclear Assoc, London, UK, 2005.
[4] K. Charman, "Brave nuclear world," *World Watch*, vol. 19, pp. 26–32, 2006.
[5] L. Echavarri, "Economic competitiveness is key for renaissance," *Nuclear Plant Journal*, vol. 21, p. 17, Mar./Apr. 2006.
[6] D. Kennedy, "New nuclear power generation in the UK: Cost benefit analysis," *Energy Policy*, vol. 35, pp. 3701–3716, 2007.
[7] IAEA, Energy, Electricity and Nuclear Power Estimates for the Period up to 2030. Vienna, Austria, IAEA, 2005.
[8] G. Watford, "Extended power uprates—Plant modifications assisting the global energy demand," in *Proc. World Nucl. Assoc. Annu. Symp. 2005*, Sep. 9, 2005.
[9] F. Nachreiner, P. Nickel, and I. Meyer, "Human factors in process control systems: The design of human-machine interfaces," *Safety Science*, vol. 44, pp. 5–26, 2006.
[10] Q. Liu, K. Nakata, and K. Furuta, "Display design of process systems based on functional modelling," *Cognition, Technology & Work*, vol. 4, pp. 48–63, 2002.
[11] K. J. Vicente and J. Rasmussen, "Ecological interface design: Theoretical foundations," *IEEE Trans. Syst., Man. Cybern.*, vol. SMC-22, pp. 589–606, 1992.
[12] C. M. Burns and J. R. Hajdukiewicz, *Ecological Interface Design*. Boca Raton, FL: CRC Press, 2004.
[13] C. M. Mitchell and R. A. Miller, "A discrete control model of operator function: Methodology for information display design," *IEEE Trans. Syst., Man, Cybern.*, vol. SMC-16, pp. 343–357, 1986.
[14] USNRC, TMI-2 Lessons Learned Task Force Final Report U.S. Regulatory Commission, Washington, DC, 1979.
[15] C. R. Pedersen and M. Lind, "Conceptual design of industrial process displays," *Ergonomics*, vol. 42, pp. 1531–1548, 1999.
[16] N. G. Leveson and C. S. Turner, "An investigation of the Therac-25 accidents," *Computer*, vol. 26, pp. 18–41, 1993.
[17] Y. Lin and W. J. Zhang, "A function-behavior-state approach to designing human-machine interface for nuclear power plant operators," *IEEE Trans. Nucl. Sci.*, vol. 52, pp. 430–439, 2005.
[18] N. Meshkati, "Human factors in large-scale technological systems' accidents: Three Mile Island, Bhopal, and Chernobyl," *Industrial Crisis Quarterly*, vol. 5, pp. 133–154, 1991.
[19] J. M. O'Hara, J. C. Higgins, J. J. Persensky, P. M. Lewis, and J. P. Bongarra, Human Factors Engineering Program Review Model U.S. Nuclear Regulatory Commission, Washington, DC, 2004, Tech. Rep. NUREG-0711 Rev. 2.

Authorized licensed use limited to: IEEE Xplore. Downloaded on January 25, 2009 at 15:35 from IEEE Xplore. Restrictions apply.

[20] J. M. O'Hara, "A quasi-experimental model of complex human-machine system validation," *Cognition, Technol. Work*, vol. 1, pp. 37–46, 1999.

[21] J. M. O'Hara and W. S. Brown, Human-System Interface Design Review Guidelines U.S. Nuclear Regulatory Commission, Washington, DC, 2002, Tech. Rep. NUREG-700, Rev. 2.

[22] B. Kirwan and L. Ainsworth, *A Guide to Task Analysis*. Bristol, PA: Taylor and Francis, 1992.

[23] J. R. Hajdukiewicz and K. J. Vicente, "A theoretical note on the relationship between work domain analysis and task analysis," *Theoretical Issues in Ergonomics Science*, vol. 5, pp. 527–538, 2004.

[24] J. Rasmussen, "Skills, rules, and Knowledge; signals, signs, and symbols, and other distinctions in human performance models," *IEEE Trans. Syst., Man, Cybern.*, vol. SMC-13, pp. 257–266, 1983.

[25] C. Perrow, *Normal Accidents: Living With High-Risk Technologies*. Princeton, NJ: Princeton Univ. Press, 1999.

[26] J. Reason, *Human Error*. Cambridge, U.K.: England Cambridge Univ. Press, 1990.

[27] J. Rasmussen, Man-Machine Communication in the Light of Accident Records Danish Atomic Energy Commission, Research Establishment Risø, Roskilde, Denmark, 1969, Tech. Rep. S-1-69.

[28] K. J. Vicente, *Cognitive Work Analysis: Toward Safe, Productive, and Healthy Computer-Based Work*. Mahwah, N.J: Lawrence Erlbaum Associates, 1999.

[29] R. J. Mumaw, E. M. Roth, K. J. Vicente, and C. M. Burns, "There is more to monitoring a nuclear power plant than meets the eye," *Human Factors*, vol. 42, pp. 36–55, 2000.

[30] J. Rasmussen, A. M. Pejtersen, and L. P. Goodstein, *Cognitive Systems Engineering*. New York: Wiley, 1994.

[31] M. Lind, "Modeling goals and functions of complex industrial plants," *Appl. Artif. Intell.*, vol. 8, pp. 159–283, Feb. 1994.

[32] A. Miller, "A work domain analysis framework for modeling intensive care unit patients," *Cognition, Technol., Work*, vol. 6, pp. 207–222, 2004.

[33] D. Prius, "Future trends in computerized operation," in *Proc. IEEE 7th Conf. Human Factors and Power Plants*, 2002, pp. 4-28–4-32.

[34] K. J. Vicente, "Ecological interface design: Progress and challenges," *Human Factors*, vol. 44, pp. 62–78, 2002.

[35] N. Lau, G. A. Jamieson, G. Skraaning, Jr, and C. M. Burns, "Ecological interface design in the nuclear domain: An empirical evaluation of ecological displays for the secondary subsystems of a boiling water reactor plant simulator," *IEEE Trans. Nucl. Sci.*, vol. 55, no. 6, Dec. 2008.

[36] T. Karlsson, H. Jokstad, B. D. Meyer, C. Nilhlwing, S. Norrman, E. K. Puska, P. Raussi, and O. Tiihonen, OECD Halden Reactor Project: The HAMBO BWR Simulator of HAMMLAB OECD Halden Reactor Project, Halden, Norway, 2001, Tech. Rep. HWR-663.

[37] F. Øwre, J. Kvalem, T. Karlsson, and C. Nihlwing, "A new integrated BWR supervision and control system," in *Proc. IEEE 7th Conf. Human Factors and Power Plants*, 2002, pp. 4-41–4-47.

[38] J. Rasmussen, "The role of hierarchical knowledge representation in decision making and system management," *IEEE Trans. Syst., Man, Cybern.*, vol. SMC-15, pp. 234–243, 1985.

[39] K. J. Vicente, "Ecological interface design as an analytical evaluation tool," in *Proc. Adv. Human Factors Res. Man/Comput. Interactions: Nucl. Beyond*, Nashville, TN, 1990, pp. 259–265.

[40] W. S. Pawlak and K. J. Vicente, "Inducing effective operator control through ecological interface design," *Int. J. Human-Comput. Studies*, vol. 44, pp. 653–688, 1996.

[41] K. J. Vicente and J. Rasmussen, "The ecology of human-machine systems II: Mediating "direct perception" in complex work domains," *Ecol. Psychol.*, vol. 2, pp. 207–249, 1990.

[42] D. V. Reising and P. M. Sanderson, "Ecological interface design for Pasteurizer II: A process description of semantic mapping," *Human Factors*, vol. 44, pp. 222–247, 2002.

[43] G. A. Jamieson and K. J. Vicente, "Ecological interface design for petrochemical applications: Supporting operator adaptation, continuous learning, and distributed, collaborative work," *Comput. Chem. Eng.*, vol. 25, pp. 1055–1074, 2001.

[44] G. A. Jamieson, "Ecological interface design for petrochemical process control: An empirical assessment," *IEEE Trans. Syst., Man, Cybern.*, vol. 37, pp. 906–920, 2007.

[45] G. A. Jamieson, C. A. Miller, W. H. Ho, and K. J. Vicente, "Integrating task- and work domain-based work analyses in ecological interface design: A process control case study," *IEEE Trans. Syst., Man, Cybern.*, vol. 37, pp. 887–905, 2007.

[46] N. Dinadis and K. J. Vicente, "Ecological interface design for a power plant feedwater subsystem," *IEEE Trans. Nucl. Sci.*, vol. 43, pp. 266–277, 1996.

[47] C. M. Burns, "Putting it all together: Improving display integration in ecological displays," *Human Factors*, vol. 42, pp. 226–241, 2000.

[48] C. M. Burns, "Navigation strategies with ecological displays," *Int. J. Human-Comput. Studies*, vol. 52, pp. 111–129, 2000.

[49] D. H. Ham and W. C. Yoon, "The effects of presenting functionally abstracted information in fault diagnosis tasks," *Rel. Eng. Syst. Safety*, vol. 73, pp. 103–119, 2001.

[50] D. H. Ham and W. C. Yoon, "Design of information content and layout for process control based on goal-means domain analysis," *Cognition, Technol., Work*, vol. 3, pp. 205–223, 2001.

[51] Y. Yamaguchi and F. Tanabe, "Creation of interface system for nuclear reactor operation—Pratical implication of implementing EID concept on a large complex system," in *Proc. XIVth Triennial Congr. Int. Ergonomics Assoc. 44th Annu. Meeting Human Factors and Ergonomics Soc.*, 2000, pp. 571–574.

[52] J. Itoh, A. Sakuma, and K. Monta, "An ecological interface for supervisory control of BWR nuclear power plants," *Control Eng. Practice*, vol. 3, pp. 231–239, 1995.

[53] H. Jokstad, ProcSee 2007 [Online]. Available: http://www.ife.no/departments/visual_interface_technologies/products/procsee/

[54] R. Welch, A. O. Braseth, C. Nihlwing, G. Skraaning, jr, A. Teigen, Ø. Veland, N. Lau, G. A. Jamieson, C. M. Burns, and J. Kwok, The 2005 Ecological Interface Design Process and the Resulting Displays OECD Halden Reactor Project, Halden, Norway, 2007, HWR-847.

[55] J. Kwok, "Ecological Interface Design for Turbine Secondary Systems in a Nuclear Power Plant: Effects on Operator Situation Awareness," M.A.Sc. thesis, Dept. of Syst. Design Eng., Univ. of Waterloo, Waterloo, ON, Canada, 2007.

[56] N. Lau and G. A. Jamieson, "Ecological interface design for the condenser subsystems of a boiling water reactor simulator," in *Proc. 16th Triennial World Congr. Ergonomics*, 2006.

[57] N. Lau and G. A. Jamieson, "Ecological interface design for the condenser subsystems of a boiling water reactor," in *Proc. 27th Annu. Canadian Nucl. Soc. Conf.*, 2006.

[58] N. Lau and G. A. Jamieson, "Numerical models in representation design: Computing seawater properties in an ecological interface," in *Proc. 50th Annu. Meeting Human Factors and Ergonomics Soc.*, 2006, pp. 245–249.

[59] G. A. Jamieson and D. V. Reising, "Cost justifying investments in advanced human-machine interface technologies I: A cost-benefit framework for the process industries," in *Proc. 48th Annu. Meeting Human Factors and Ergonomics Soc.*, 2004, pp. 1179–1183.

[60] J. Errington, D. V. Reising, P. Bullemer, T. DeMaere, D. Coppard, K. Doe, and C. Bloom, "Establishing human performance improvements and economic benefit for a human-centered operator interface: An industrial evaluation," in *Proc. 49th Annu. Meeting Human Factors and Ergonomics Soc.*, 2005, pp. 2036–2040.

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