Cognitive
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Laboratory

The 2005 Ecological Interface Design Process and the Resulting Displays

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HWR-847

OECD HALDEN REACTOR PROJECT

THE 2005 ECOLOGICAL INTERFACE DESIGN PROCESS AND THE RESULTING DISPLAYS

by

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Institutt for energiteknikk
OECD HALDEN REACTOR PROJECT

Title

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Abstract:

The design principles called Ecological Interface Design (EID) provide a theoretical basis and design guidance for developing novel displays for monitoring and controlling complex systems such as industrial processes. EID is a central research topic in the Halden Reactor Project (HRP) research programme on innovative Human System Interfaces and this HWR describes the analysis phase, the display design phase, the completed display designs and operator feedback for the HAMBO BWR simulator EID displays.

The work domain analyses and the display design were conducted simultaneously in the three work groups, the HRP, the University of Toronto and the University of Waterloo. This allowed us to investigate how different types of teams perform Work Domain Analyses or design displays that are supposed to function together, and what challenges can appear when teams working geographically distributed are trying to create compatible Abstraction Hierarchies and displays.

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1. INTRODUCTION

The design framework called Ecological Interface Design (EID) were formulated around 1990 by Jens Rasmussen and Kim Vicente [1] and provide a theoretical basis and design principles for developing novel displays for monitoring and controlling complex systems such as industrial processes. These principles have generated a lot of interest, but the number of representative applications of this approach is still limited. EID is a central research topic in the Halden Reactor Project (HRP) research programme.

The purpose of the EID project is to find out whether EID-based displays will enhance performance of control room operators, by running experiments with experienced operators in the HAMMLAB facility. A first large-scale experiment with EID displays were conducted in January 2006. This experiment should be seen as a first step in a validation process.

2. ECOLOGICAL INTERFACE DESIGN BACKGROUND

Some find the “Ecological” part of Ecological Interface Design unusual, as ecology is usually associated with interaction mechanisms of biological systems. It therefore seems strange that this is connected to interface design. However, the Ecological in EID originates from a field of psychology known as Ecological Psychology. A fundamental premise in this field is that the study of any behaviour should not only analyze the behaviour of the individual in isolation, but also analyze the constraints of the environment that shape its behaviour. The environment and the individual must be understood as a joint system of mutual constraint and thus studied together. This view is also seen as relevant for understanding (and thus for analyzing) more intellectual behaviour such as monitoring, control and problem solving in process control, where it implies that one should not just study the human worker and what he does; it is equally important to understand the constraints in his work domain that shape the worker’s actions.

Ecological psychology also emphasizes the power of direct perception and action in natural behaviour. In a natural environment the human is able to directly perceive large amounts of relevant information in its surroundings and use this information effortlessly to shape its behaviour. For instance, a skilled car driver normally perceives his or hers "field of safe travel" directly and fluently without any conscious, high-level cognitive processing. As opposed to typical work involving computer tools, the kind of behaviour involved in basic car driving is efficient, reliable and effortless.

The so-called "ecological approach" to human-system interfaces is based on the idea of supporting the same kind of effortless, adaptive behaviour found in physical environments also in the cognitive work found in a modern control room or airplane cockpit, etc. The ecological approach offers an alternative understanding of human work and how one can design systems to best utilize the strengths of human beings in a work system. Humans are very capable in natural environments because we effectively adapt to the constraints of the environment. An ecological interface aims to provide an "artificial environment" that has the kind of characteristics that let workers develop powerful perception and action capabilities and apply them in their work when dealing with the tasks and problems in complex work domains such as process control.

An important idea in ecological interface design is therefore to "make the invisible visible", or to show explicitly everything that must be perceived, considered and understood correctly in order to select appropriate behaviour under any circumstances. In doing so, these interfaces aim to support the development of capabilities whose usefulness and relevance also extends to dealing with unanticipated situations and thus supports operators also in such important, but hopefully rare situations [2].

The EID framework is based on Work Domain Analysis (WDA) to identify interface content and the Skills-Rules-Knowledge (SRK) taxonomy to guide the visual design of the interface. The WDA allows the designer to identify content that will induce a correct mental model of the process; while supporting the SRK based behaviour types when designing the visual form of the interface helps support operator cognitive skills when interacting with the process.

3. THE HRP EID PROJECT

Even though EID has generated a lot of interest, the number of applications of this approach for complex systems is still very limited. There has been some EID research with access to expert users of complex systems [3], but getting this kind of access has generally been a problem. In the HRP we have the possibility to address both these issues. We have access to high fidelity simulators of complex nuclear processes and we have a long tradition of cooperation with the nuclear industry that allows realistic experimental studies with nuclear process operators. An HRP effort in this was therefore seen to have the potential to bring significant contributions to EID research, and also the application and further development of the ideas of EID that are highly relevant for the nuclear industry.

In 2003 and 2004 the HRP EID project concentrated on designing prototype EID displays for the secondary side of the PWR process using the FRESH simulator [4]. A user test with professional operators from the Ringhals plant was also conducted. In 2004 cooperation with the University of Toronto and the University of Waterloo was initiated and it was decided to attempt to design a more complete set of EID displays on the HAMBO BWR simulator and run a full scale experiment for these displays. The reason for changing from the FRESH simulator to the HAMBO simulator was that the instructions for HAMBO were in Swedish and therefore more easily usable by Swedish operators and in HAMBO it was possible to extract process information directly from the simulator that would not be accessible from process plant sensors. To better be able to use the knowledge and experience gained from working with FRESH it was decided to continue with concentrating on the secondary side of the process. The experiment is described by Gyrd Skraaning et al. [5].

The secondary side was divided into three parts that are reasonably equal in terms of complexity, with the University of Waterloo being responsible for analysing and designing the displays for the turbines, the University of Toronto for the condenser and HRP for the condensate and feedwater systems. Dividing the project in this manner worked well. Another seemingly logical way of dividing the work, between the analysis phase and the design phase, has proven in past EID projects to be extremely difficult since it is considered necessary for designers to go through the analysis process in order to understand the process being designed for.

4. THE ANALYSIS PHASE

4.1 Conducting the Work Domain Analysis for identification of information requirements

The work domain analyses were conducted simultaneously in the three work groups. Communication and coordination between the groups were mostly done weekly, through net-conferencing, teleconferencing and one face-to-face meeting. These meetings were necessary to ensure that the groups had a comparable understanding of the analysis process, that the abstraction level structures were the same so that the information described at each level were comparable between the groups, and that the language used to describe this information were comparable. Even though it was desired that the groups had a comparable view on the analysis process, it was important that each group found their own way of structuring their analysis, so that it best suited their experience and background knowledge.

The WDA is the process of decomposing the system, in this case the secondary side of the HAMBO simulator process, and thereby creating an Abstraction Hierarchy. The WDA decomposes the system in two dimensions, part-whole and level of abstraction. Moving in the part-whole dimension reveals what a system consists of from viewing the whole system to subsystems and finally the individual components. The level of abstraction decomposition shows the connection between the goals (ends) of the industrial process and the physical configuration that implements them (means).

The abstraction hierarchy suggests five levels of abstraction relevant for process control [6]

- The purposes for which the plant was designed (Level 1 decomposition, “Functional Purpose”)
- The mass and energy topology of the plant (Level 2 decomposition, “Abstract Functions” or “Priorities/values”)
- The generic functions that implement that topology (Level 3 decomposition, “Generalized Functions” or “Purpose related functions”)
- The plant equipment that realizes those functions (Level 4 decomposition, “Physical Function” or “Object-related processes”)
- The spatial location and appearance of that equipment (Level 5 decomposition, “Physical Form” or “Physical Objects”)

Today's single-sensor, single-indicator based interfaces typically present the plant only at the level of physical function, which is usually good enough for operating the plant in familiar or procedure supported situations. Knowledge based problem solving in such systems is based entirely on the operator's mental model established through education and training, and requires mental integration of the available low-level information in order to obtain a complete understanding. The problem with this is the possibility that the mental model may be incorrect or incomplete, and there may be too much effort involved in using it efficiently in critical situations. The fact that operators engaged in knowledge based problem solving will need to understand and relate to the plant state at any level of abstraction, implies that the plant state should be visualized directly at all levels of abstraction. The abstraction hierarchy is therefore a framework for structuring different models that capture relevant constraints in the work domain that shape the operators activities, whereas other design methods focus on analysis of predefined ways to perform activities.

4.2 Use of simulated sensors

In the experiment the EID displays were compared to the existing HAMBO displays and also a stripped down version of the HAMBO displays. The existing HAMBO displays are considered to represent advanced computerized design, i.e. state-of-the-art computerized displays currently available in NPP control rooms. They contain all information available in traditional displays and are mostly based on a P&ID structure but also have some task based elements. They also contain graphical units that are made possible by computer technology such as temporal information and aggregated information. The stripped down version represents a Traditional computerized design, i.e. computerized version of traditional displays found in most NPP control rooms. They also contain all information available in traditional displays and have the same design structure as the full HAMBO displays, but do not contain graphical units that are only made possible by computer technology.

The HAMBO simulator is a high fidelity simulator where it is possible to extract process information that is not available from the process sensors in the real plant. The HAMBO displays and therefore the stripped down version of these only contained information that is available in the real process plant. The reason for this was that the HAMBO was meant as a computerization of the Forsmark power plant existing interface which is largely wall panel based. The HAMBO displays therefore contain the data that is present in the Forsmark interface and are structured so that they resemble, as much as is possible on a computer display, the original layout of the wall panels.

It was decided however, to include in the EID displays some process information extracted from the HAMBO simulator that would not be available in the real plant. One of the proposed major contributions of the EID framework is that it defines an information content that supports different and more effective cognitive strategies than traditional ways of defining and displaying content. EID displays therefore have different and usually larger information and sensor requirements than traditional displays. While a lot of this information content may to a large extent be derived from the same single sensors used in traditional displays, it also may ultimately be necessary to use additional process information within reasonable limits. Since the purpose of this experiment is to discover whether EID displays leads to better performance, it was decided to create as optimal as possible EID displays. To be able to do this, information that is available from HAMBO but not from the process plant sensors is included.

This makes it somewhat difficult to determine whether the performance benefits of EID found in the experiment, if any, is caused by EID having a larger information requirement or whether the EID displays needed more information than what was practically or economically possible with the original panel interface and therefore HAMBO interface. However, operators and others could during the design and start-up of the plant recommend adding sensors, and therefore the amount of sensors has been influenced by users and other stakeholders who have used an informal and experience-based cost-benefit analysis to decide whether there is a need for additional information in their displays. It can therefore be argued that this analysis is part of the framework that is used when designing traditional displays which is being compared with the EID framework in this experiment.

The EID design process has aimed to make reasonable assumptions about adding sensors beyond what exists in the HAMBO simulator today, and additions have been made with the following limitations:

- Only sensors that could have been specified at the time of designing the plant are used.
- Control volumes of mass balances have been defined so that the need for additional sensors is minimized.
- Sensors have not been added in process areas considered less important.
- The vast majority of sensors data shown in the EID display are found also in the existing displays.

4.3 The HRP analysis

The HRP analysis was shaped by the fact that the personnel were experienced designers, but with limited experience with EID design. In addition, the designers had some degree of experience with the nuclear process and extensive experience in working with process operators. They therefore knew a lot from experience about what process operators generally value and dislike when it comes to process displays and what nuclear plant operators' needs are. They also had easy access to process experts and the HAMBO simulator. In addition, through this, the design team knew that the operators did not view the condensate and feedwater systems as being safety critical since the system has few possibilities for generating critical incidents. This was a result of the decision to develop a design for the entire main secondary side which includes both critical and non-critical areas.

Altogether, this resulted in that the team had a high focus on what would be practically possible for the operators to learn and accept for perceived non-critical systems within available training time. The HRP design team therefore attempted to create displays that demonstrated the capability to support operators during incidents that could be perceived as important (or relevant, at least) by the operators. This means that the designers did not perceive all of the process areas included in the WDA as equally appropriate to visualize in the displays, even though this was against the EID philosophy since the WDA does not differentiate between important and unimportant process areas. The result was that the design team did not complete the WDA in areas that were deemed to be largely unimportant to running the plant at normal operation and where the effect of an accident or safety breach would be limited. Designing a display with content that the operators would not find relevant or would find difficult to learn in the time available would have negative effects on their performance during the experiment.

Another difference between HRP and the other design teams' analysis processes was that the HRP design team operated with level 4 part-whole models (see Figure 1.). The reason for this is that the feedwater systems have a lot of important equipment organized in parallel such as pumps and heat exchangers. The level 3 decomposition does not include such parallelism, while a regular P&ID diagram in addition to showing equipment in parallel also shows equipment that is not used in normal operation and equipment that can not be monitored and controlled from the control room, and therefore does not need to be visualized in the EID design.

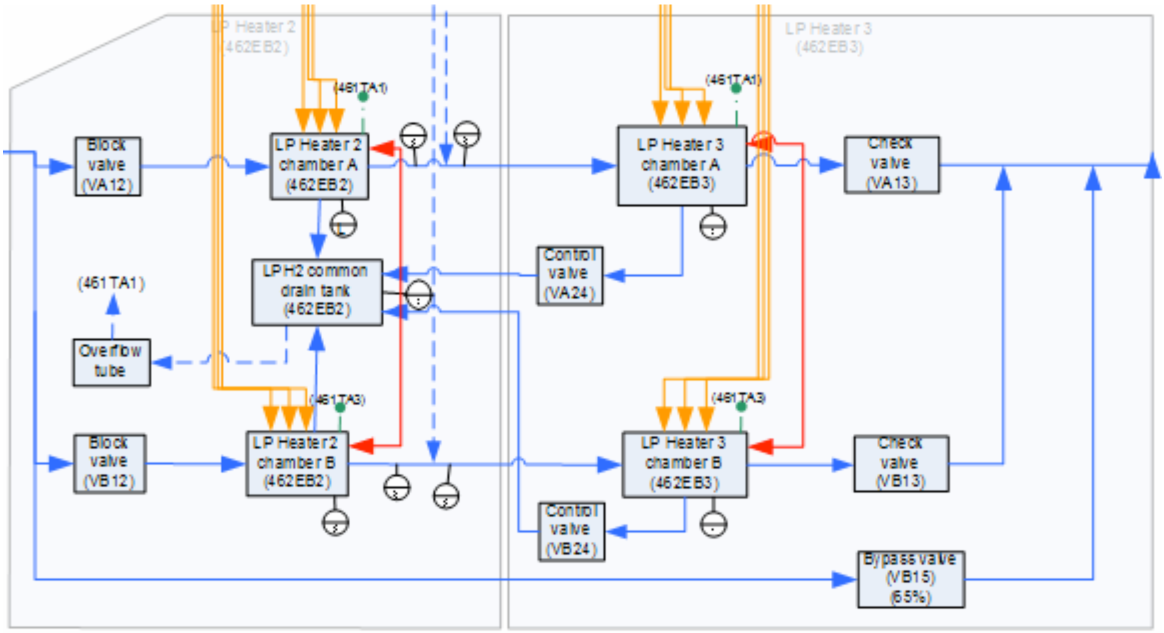

Figure 1. Excerpt of the HRP Level 4 WDA analysis

4.4 The University of Toronto (UT) and University of Waterloo (UW) analysis

The University of Toronto assigned the analysis and design work of the condenser area to a student at his Master's study. He had two relevant structured courses: (1) Ecological Interface Design (EID) and (2) Cognitive Work Analysis (CWA). He had neither practical experience in interface design for complex systems, nor experience from the nuclear industry.

The UT project member primarily relied on [1] to guide his work domain analysis and design. He also used [6] as a secondary reference. A UT professor provided academic support to the analyst/designer on any theoretical issue related to the EID framework.

The UW project member was also a student who had a very similar background to the UT member. However her primary source was [6] while the work by Vicente and Rasmussen functioned as a secondary reference to guide her work domain analysis and design. Academic support was provided by a UW professor on any theoretical issue related to the EID framework and she mostly relied on the same sources as the UT member. The UW professor also took advantage of her past experience in larger scale nuclear and petrochemical projects which is also the source of the part-whole breakdown strategy used in the project by all the teams.

As for populating the work domain analysis, the UT and UW analysts relied on three sources: (1) Forsmark 3 nuclear power plant documentation, (2) process experts, and (3) science literature. The key plant documentations were Piping and Instrumentation Diagrams (P&IDs) and the subsystems specifications. The analysts had limited access to a process expert through emails. In addition, two teleconference and two face-to-face meetings were conducted to clarify the details of the work domain. They used public science literature to learn about general principles governing the plant processes as described by the process experts and plant documentation.

The UT analysis approach was typically academic. That is, the WDA was conducted in a manner as formal and as close as possible to the prescription of the EID literature. There was virtually no pragmatic consideration such as implication for design. The analysts assumed the claims of EID to be true for the analysis phase (and design phase) so that the final interface reflects the framework as much as possible. The benefits and functions of the WDA were not formally considered or verified until the analytical evaluation of the final interface. The UW member is assumed to have taken a very similar approach.

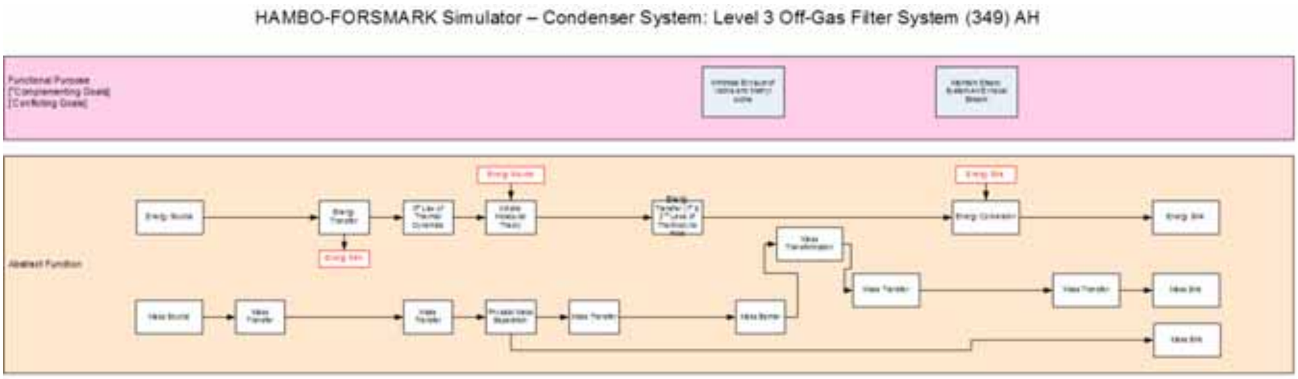

Figure 2. UT Abstraction Hierarchy visualizing the Level 3 Functional purpose and Abstract function of the Off-gas filter system

5. THE VISUAL DESIGN PROCESS

5.1 The HRP visual design process

The HRP design team had extensive experience in designing and introducing novel displays for professional operators in industry, and this clearly influenced the goals and approach they used. The design process was very much a team effort, and the two designers were able to capitalize on their previous experience from working jointly on interface designs. By altering between individual and joint design sessions, the different perspectives and perceptions of the two designers were effectively utilized in a rapid iteration cycle where ideas were continually created, evaluated, improved or rejected through a cycle of prototyping and “micro-experiments” triggering reflection and redesigns.

The WDA was initially used to identify types of information content (goals, functions, equipment and constraints) and a conceptual design was created featuring the initial versions of the single-variable and complex configural display elements required to visualize this type of information content. In parallel with this it was sought to establish an overall structure that also reflected the topological and means-ends relationships between display elements. Further into the detailed design phase the WDA was used as the “blueprint” for developing displays with complete information content according to the analysis.

Based on their prior experience in design and evaluation projects, the HRP designers created (implicitly or explicitly) additional, self-imposed design constraints on several issues on which the EID literature is silent. Navigation demands were sought minimized by developing a minimum number of displays with high information density. Another issue was to carefully consider how sensitive new graphical displays elements would be to significant plant deviations as compared to the sensitivity of existing alarms and the existing alarm-based work strategies that operators would have. Another major issue was how new displays need to be learnable within the limited training time available in preparation for experimental studies. This calls for reuse of already familiar display elements whenever possible and prioritizing novel display features that visualize constraints and relationships that operators will readily accept as relevant to monitor. This implied that the designers were reluctant to introduce simulated sensors in what operators consider being of minor importance within a subsystem that itself is regarded as non-critical in the overall safety perspective that guides their problem solving strategies during plant disturbances.

The team had more frequent and informal contact with domain experts and operating experience in Halden, and their understanding of many of the issues described here emerged from this interaction with domain experts and thus supplemented the domain knowledge explicitly captured in the WDA in shaping the final design.

5.2 The UT and UW visual design process

The design by the UT and UW project members underwent an equally academic approach as the WDA. The designers followed the prescription of the EID literature formally without any explicit, practical considerations. In essence, the designer attempted to completely map the work domain model as captured by the WDA onto the interface. In addition, the visual forms were designed in a way that operators did not need to engage at levels of cognitive control (i.e. Skills, Rules, and Knowledge) higher than necessary. Note that the UT designer did vary his attention across different parts of the plant in the design phase because the WDA implicitly suggested relative importance amongst different parts of the plant. The designers did not account for the attitude or training requirements of the plant operators towards any advanced/unconventional visualization. The designers also generally did not factor in any instrumentation constraints, such as acquiring energy values for various process points, even though such parameters may be unfamiliar to the operators. However the UW designer chose not to visualize the entropy through the turbine systems as this would have been difficult to calculate with the existing constraints.

Although instrumentation constraints are not treated in the same manner as in the industry, process information was inserted strategically to minimize the additional demand on sensors or derived/simulated information (e.g. enthalpy values). The aforementioned factors were excluded from design considerations because the designers tried to develop an interface reflecting the nature of the EID framework as much as possible.

6. FINAL DISPLAYS

The existing HAMBO displays are similar to the wall panel based interface used at the Forsmark power plant. To make the new designs easier to understand and use for operators, it was decided that the graphical units used in the existing HAMBO displays were to a large degree to be re-used for the EID displays. This would also reduce the performance effects that could be created by having different levels of usability and learnability in the display types.

The HAMBO graphical units were mostly at a low abstraction level (usually at the Physical function level) and therefore new graphical units had to be designed to visualize higher abstraction information. Adding new graphical units to the display also meant that there was less space for the lower abstraction information and therefore the HAMBO graphical units were compressed, both by making the graphical units themselves slightly smaller and by packing the units closer together. The downside to this is that the EID displays may suffer from lower usability due to the clutter and the reduced readability this creates.

6.1 The turbine displays

The two turbine displays depict process flows between the reactor and condenser in a left-to-right manner. Figure 3 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 (Figure 3a). Below the reactor pressure trend graph are the enthalpy, temperature, and pressure profiles across the entire turbine area (Figure 3b). Figure 3c is a contol valve overview describing the behavior of control valves on the mimic diagram below. This was originally shaped in a form similar to a Polar star, but this was changed so it more closely matched the control valve overviews in the condensate and feedwater displays. At the bottom right is a mimic diagram depicting steam flow discharged from the reactor to the high-pressure turbine (Figure 3d). Mass balances are integrated in the mimic diagram to detect coolant/steam losses.

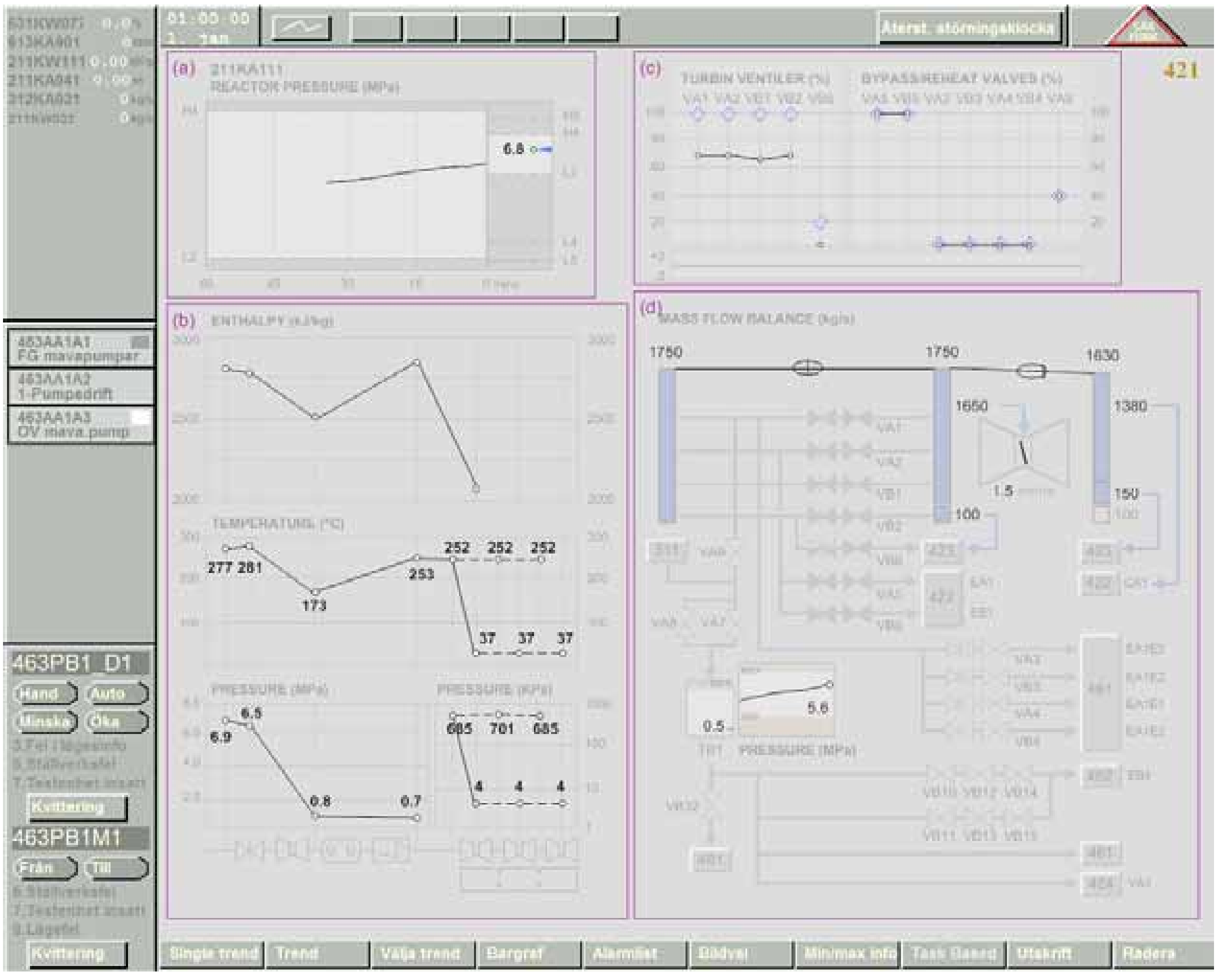

Figure 3. The HP turbine system. Visualizes the main flow from the reactor to the LP turbines and an overview of the turbine area

The ecological interface for the turbine area continues on Figure 4. The top left of this display is another valve monitoring unit for the control valves (Figure 4a) in the mimic diagram (Figure 4c) appearing below. To the right of the valve monitoring unit are trend graphs of 16 major storage tanks (Figure 4b). The bottom half of this display is a mimic diagram integrated with mass balances, depicting process flows from the high-pressure to the low-pressure turbines (Figure 4c). The bar graph at the far left (which replicates the one at far right of Figure 3d) shows steam exhaust from the high-pressure turbine, while the graph at the far right shows steam output to the condenser and feedwater areas. The exhausts of the low-pressure turbines are dumped into the condenser for latent heat extraction as illustrated by the downward arrows from the three turbine icons to the three-chamber condenser icon in Figure 4c. For further description of some graphical forms in the ecological interface of the turbine area, see [7].

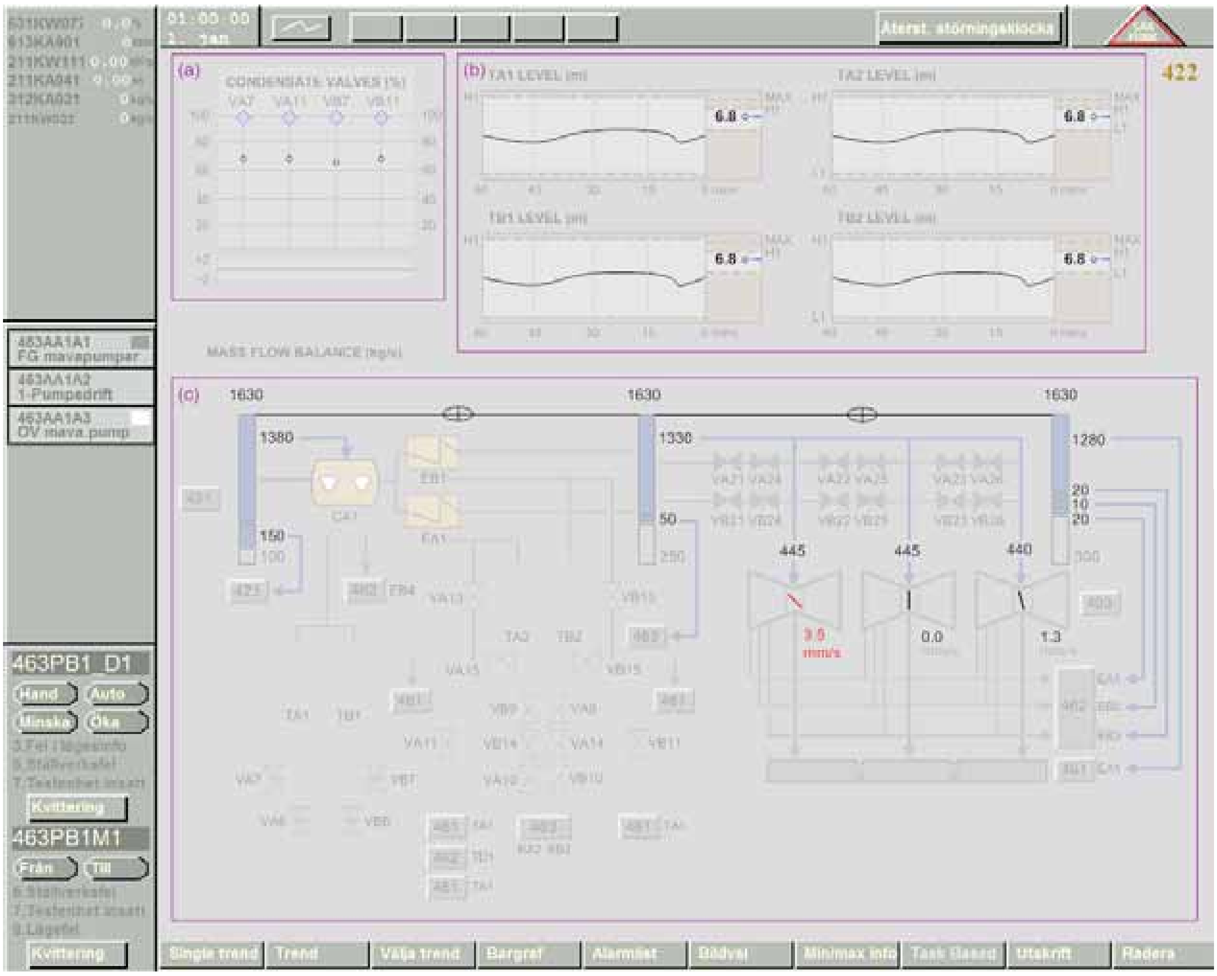

Figure 4. The LP turbine system (system 422). Visualizes the main flow from the HP turbine to the condenser.

6.2 The condenser display

The ecological interface for the condenser area (Figure 5) depicts the operations of the condenser and its supporting subsystems. At the top left are start-up ejector components for reducing pressure during plant start-up (Figure 5a). Directly below is the three chamber condenser icon embedded with level and pressure trend graphs (Figure 5b; Appendix 3). To the left of the condenser icon are the regular ejector components with two identical valve monitoring units (Figure 5c). At the top right are two tanks embedded with pressure-temperature plots to illustrate the re-combination process (Figure 5d; Appendix 5). The bottom right is a seawater monitoring unit showing the changing properties of seawater across the condenser as well as the operating conditions of the seawater pumps (Figure 5e; Appendix 2). 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 (Figure 5f; Appendix 6). 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 (Figure 5g; Appendix 4). Beside the pressure-temperature plot are arrows pointing to three condensate pumps, which draw condensate from the condenser hotwell for the feedwater area. See [8, 9] for more detailed descriptions.

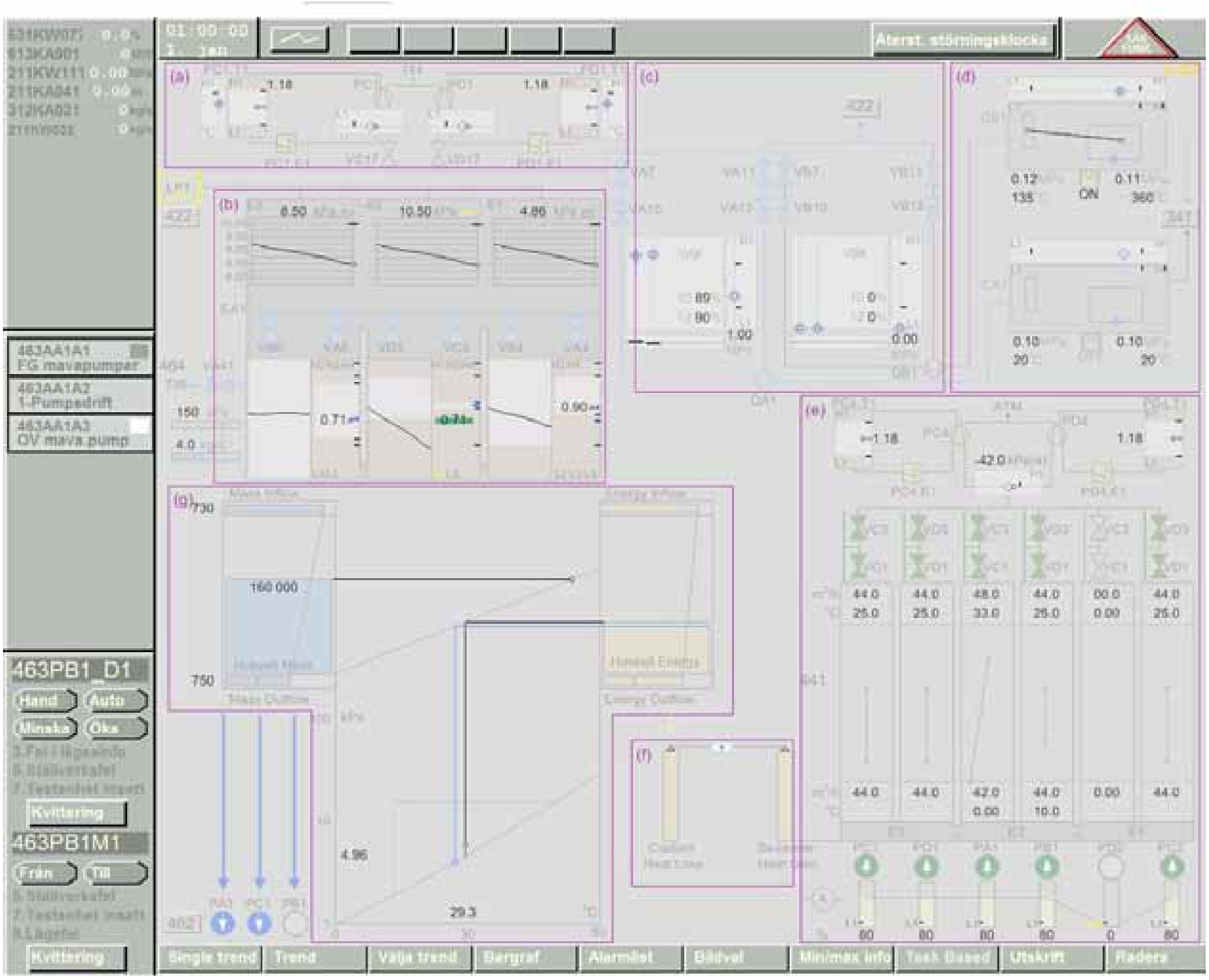

Figure 5. The condenser display. This visualizes the main flow in and out of the condenser, the seawater system another systems necessary for operation of the condenser.

6.3 Condensate and Feedwater displays

The condensate and feedwater displays depict the pressurizing and pre-heating processes between the hotwell and the reactor. Both displays orient the process flow from right to left.

Figure 6 shows the condensate display. The middle region is a mimic diagram illustrating the process flow from the condenser icon to the feedwater tank icon (Figure 6c; Appendix 7 and 9). The top right is a plot describing the condensate pump operations in drawing condensate from the condenser hotwell (Figure 6a; Appendix 7 and 8). 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 (Figure 6b; Appendix 10). The bottom region below the mimic diagram is a temperature profile that illustrates heat exchanges of condensate with bleed steam (Figure 6d; Appendix 11).

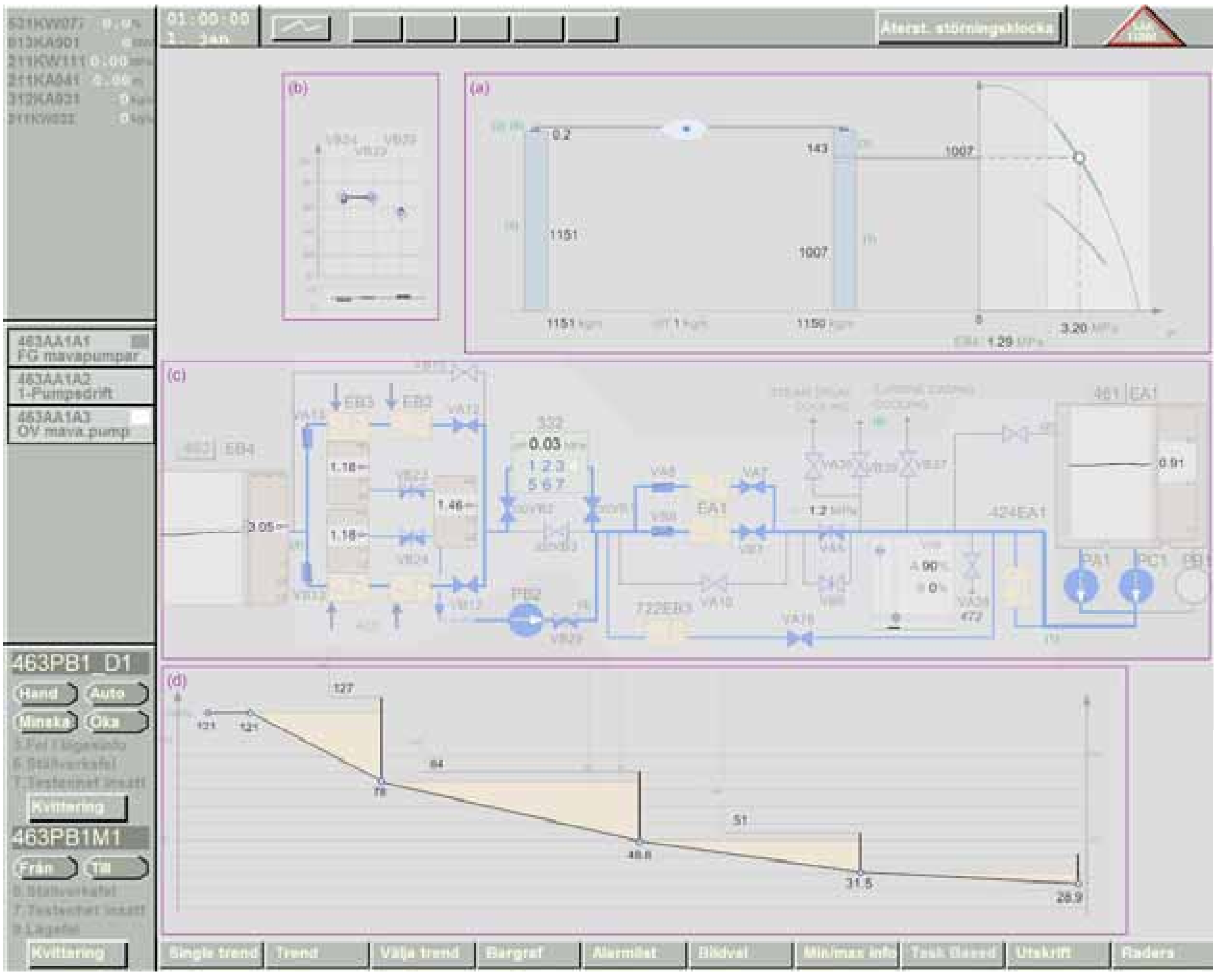

Figure 6. The condensate display. This visualizes the main flow from the condenser to the feedwater tank.

The ecological interface of the feedwater area continues in Figure 7. The mid-horizontal region, Figure 7c, is a mimic diagram showing the components from the feedwater tank to the reactor. Similar to Figure 6, the top region shows feedwater pump graphs, a mass balance for the control volume (Figure 7a; Appendix 12), and a valve monitoring unit (Figure 7b; Appendix 10). The bottom-horizontal region is another temperature profile illustrating heat exchange processes of feedwater (Figure 7d; Appendix 11).

Figure 7 depicts part of the reactor containing valves and a reactor water level trend graph. This overview of the ecological interface (Figure 3 to Figure 7) presents the basic appearance of the design, however, this, in itself cannot fully exemplify the EID framework. Detailed discussion of selected graphical units is necessary to demonstrate how the WDA and SRK taxonomy contribute to this interface and to interface design for complex systems, in general. This is covered in the appendix.

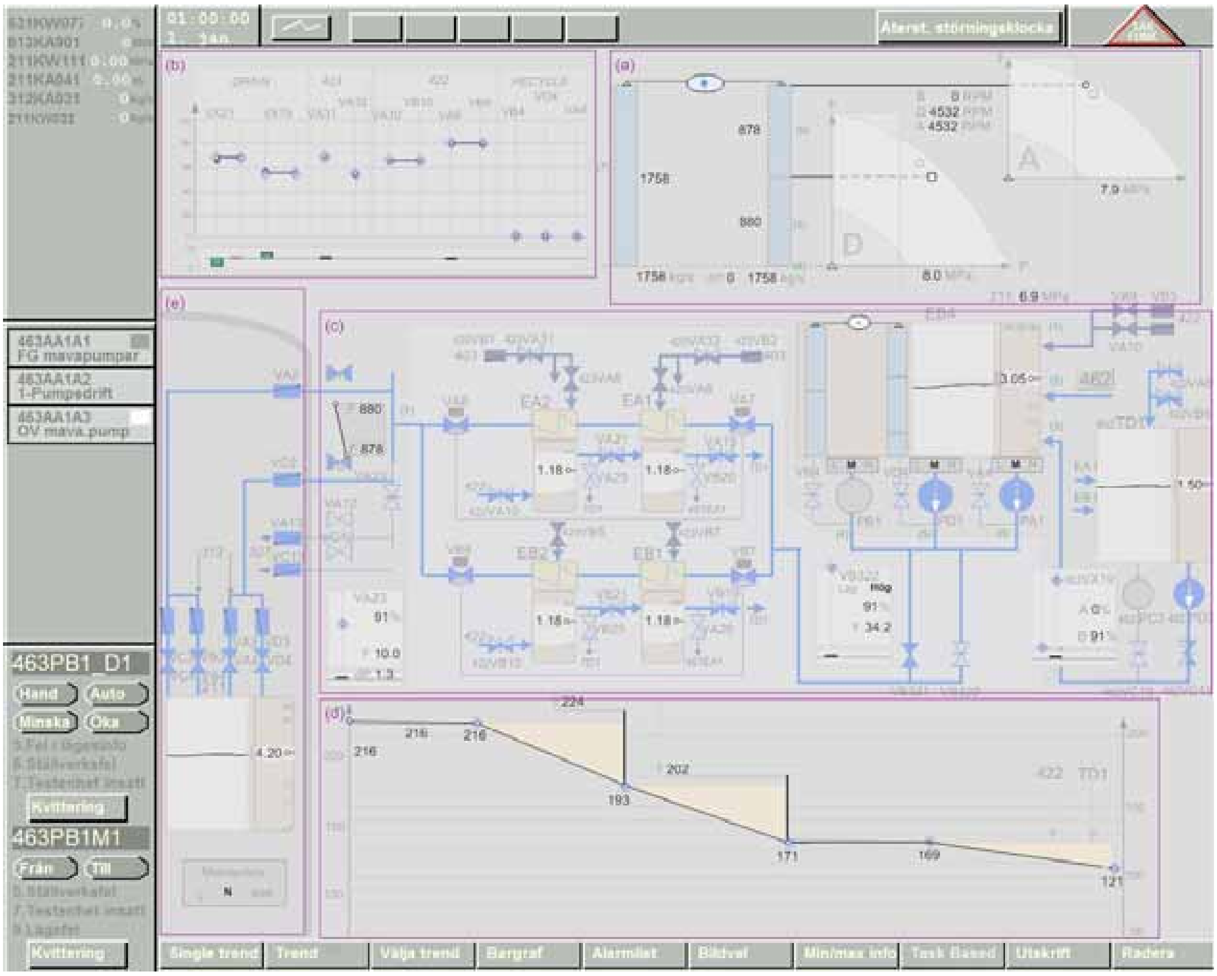

Figure 7. The feedwater display. This visualizes the main flow from the feedwater tank to the reactor

7. CHALLENGES AND LESSONS LEARNED

Challenges experienced during the analysis and design phases were at least somewhat related to the geographical distance between the design groups. In fact, the student members from UT and UW did not have an opportunity to visit Halden to see HAMMLAB or meet the process expert and the design implementer face-to-face during the design phase. The HRP design team met with the Canadian teams two times, but these was the only times the three teams met during the analysis and design phases. When we, in addition, consider that the work processes used by the University of Waterloo and University of Toronto teams differed substantially from the work processes of the HRP team, it is not surprising that some difficulties were encountered.

The main challenges that were encountered from a HRP point of view were:

- Prototypes were designed using Microsoft Visio. Difficulties were experienced when translating the designs to ProcSee, which is the tool used for implementing interfaces on the HAMBO simulator. It can be assumed that the difficulties stemmed from a different understanding of how the prototypes should be described so they could be most easily be implemented in ProcSee and who should be responsible for gathering the information (e.g. heat capacities, tank volumes etc.) that were needed to implement the displays. It was often difficult for the implementer to know where to find the needed information and also to know how accurate the information had to be to make the graphical units function as intended. These problems would have been greatly reduced if the Canadian design teams, who did not have any prior experience with ProcSee, had more knowledge about how ProcSee worked and thereby the information required by the implementer. Having a template for design specifications in advance or more direct communication between the designer and implementer would also have been practical ways to reduce this problem. In addition, if the teams had been assigned responsibility for acquiring the information needed for implementation, this would have saved time and also better streamlined the implementation phase.

- It was difficult to establish the three design groups as one common team. The long distances involved reduced the possibility of the teams communicating frequently and the lack of regular face-to-face communication made misunderstandings possible. In addition, the HRP team’s background of being experienced designers with little prior knowledge of EID compared to the project members of the Canadian teams with little prior design experience but extensive knowledge of EID gave the groups different understanding of what had to be done in the project and the work processes needed to reach these goals. It was also unfortunate that the project members of the Canadian teams were not given the opportunity to visit IFE in Halden before the project and seeing HAMMLAB and HAMBO first hand.

8. OPERATOR FEEDBACK

Individual feedback from operators on the interface designs was received during debriefing interviews performed by VTT [10]. From these interviews it was found that many of the operators had previous experience with the Hambo simulator and therefore preferred Hambo's well known displays. In contrast, one operator without previous HAMBO experience preferred EID. However, the operators generally felt that the EID displays were too full of information and that the information was too tightly packed together.

The operators liked some of the EID units such as the valve overviews and the mass balances. However, they found it difficult to use more complex EID units such as the condenser efficiency monitoring unit. They felt that the EID units were most suited for detecting anomalies but that it could be difficult to figure out what caused the anomaly and what corrective actions should be carried out. They also felt that there was a lack of training and that this influenced their performance. This especially applied when using the EID displays as these were not familiar to the operator and they contained more information than the other display types. Other comments were that:

- The design of the tank units made it difficult to compare levels in different tanks

- Pump curves were understandable but not very useful

- Feedwater and condensate temperature profiles could be useful under stable conditions but that they probably used up too much space compared to their usefulness
- Enthalpy/temperature/pressure profiles are useful for finding disturbances, but the profiles would be easier to use if changes could be tracked on the displays
- Some graphical units could be more suited for expert programs used by engineers or other staff outside the control room or on support displays

Operators also commented that some of the information that was presented in the EID displays was irrelevant, but this may also be due to the scenarios used. Since the experiment scenarios were developed independently of the displays so that the display design did not influence the scenario design, some of the information presented on the displays would be irrelevant for the scenarios.

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APPENDIX

The appendix consists of descriptions of all the main graphical units designed for this experiment that are at a higher abstraction level than “physical function”. These types of units are part of what distinguishes EID from other design concepts.

Appendix 1: Control Valve overview

Appendix 2: Seawater

Appendix 3: Condenser Instrumentation

Appendix 4: Condenser Efficiency

Appendix 5: Re-combiner

Appendix 6: Latent Heat Transfer

Appendix 7: Mass balance

Appendix 8: Condensate pumps

Appendix 9: Condensate tank

Appendix 10: Valve information unit

Appendix 11: Temperature profile

Appendix 12: Feedwater pumps

Appendix 13: Flow balance

Appendix 1: Control Valve overview

The WDA identified that the functional purposes "*Maintain feedwater tank temperature*" and "*Supply feedwater at desired temperature to reactor*" are achieved by means of mass and energy transfers at the abstract function level, which are in turn realized by means of generalized functions of heating and mixing. And these functions are supplied by various valves, heat exchangers and tanks at the physical function level. However, it was found that information requirements derived from the abstract and generalized function levels were neither supported directly by available instrumentation, nor were any functionally related variables available to allow reliable derivation of the missing data. But from the highly detailed level 4 Part-Whole, which reveals detailed configuration of individual piping and valves, a number of information requirements were identified and found feasible: Flows in parallel bleed lines should be equally distributed, which may be verified by monitoring corresponding control valves in parallel lines to see that they have the same percentage opening. The steady-state expected positions for the automatically controlled valves are known for each reactor effect level, and serve as references from which deviations may be detected. This is in fact unlike most other areas of process control, and is due to the highly optimized and closed loop process found in nuclear power plants, which leads to extremely stable and predicable operation. The measured valve position should equal the position set point from the turbine control system, and the control valves have position feedback measurements to support the detection of discrepancies that may indicate faults. The display graphics shown in Figure 8 was designed provide a compact overview of a group of valves:

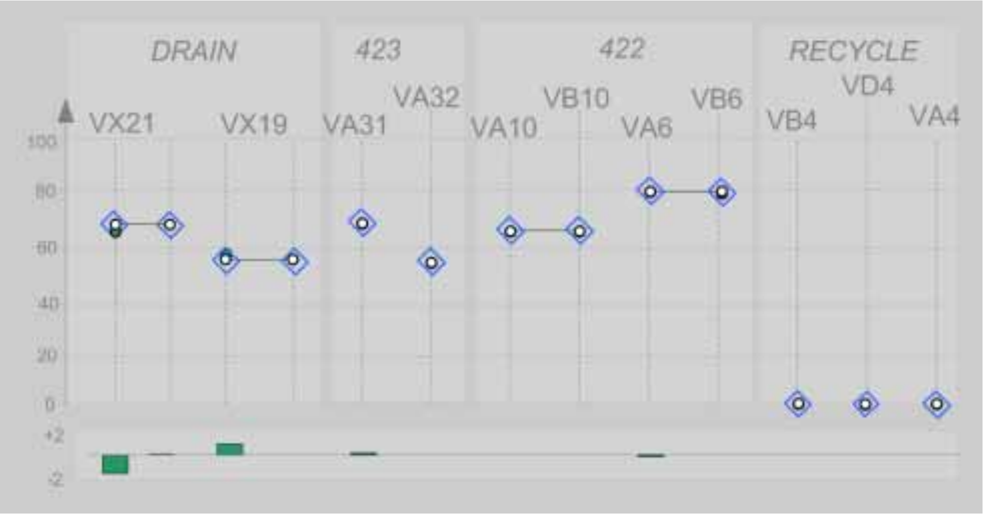


Figure 8: Control Valve Position Graphics. In this example the position of 13 control valves are shown (circles) in relation to their expected postitions (blue diamonds). Bar-graphs below show discrepancies between control signal output and actual valve positions.

The position of each automatically controlled valve is shown by a small circle that rises vertically corresponding to 0-100% valve opening.

Expected valve position for the current reactor effect is shown by the superimposed blue diamond symbol. Under normal conditions, all circles will be located inside their respective diamonds. Pairs of valves belonging to parallel flows are placed next to each other in the display and are connected by a line. The line will be horizontal in normal conditions i.e. when the flows are equally distributed and valves are functioning properly. In the lower part of the graphic there is a green bar graph representing the difference between controller output and actual valve position for each valve. The bar-graphs will generally not be seen during fault-free operation, while a stuck valve or similar fault condition will leave a visually salient indication of the discrepancy.

Appendix 2: Seawater

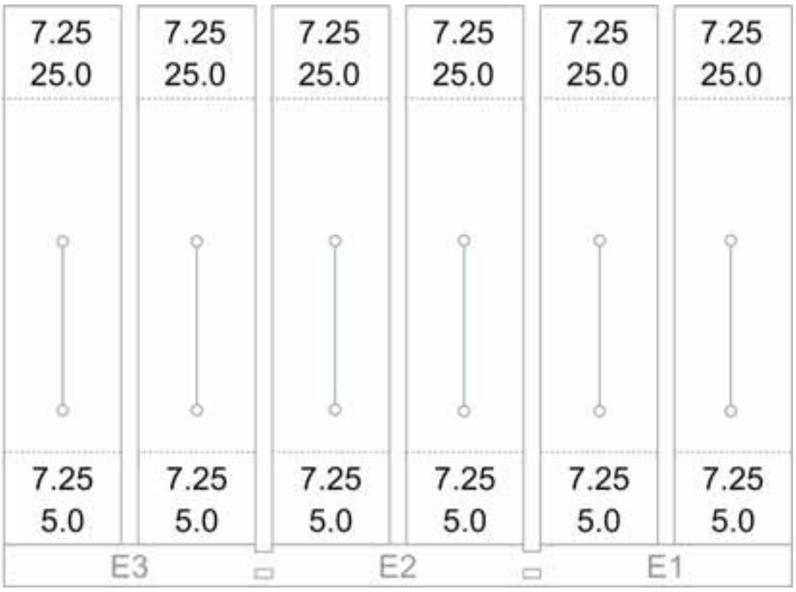


Figure 9: Seawater monitoring unit integrating six temperature-flow rate graphs.

Figure 9 presents the graphical form for monitoring seawater properties across the condenser. Changes in seawater properties are useful to infer operating conditions of the condenser during the condensation process. The pertinent domain information for this form were discovered in the AH model of the Main Cooling Water System (441) at Level 3 part-whole decomposition in the condenser area. In particular, the generalized function and physical function levels are relevant for this graphical form.

The relevant functional purpose is to satisfy condensate demand of the feedwater area. The means to achieve these purposes are through mass and energy conservation laws at the abstract function level, as condensate can be converted from turbine steam input by energy transfer. These two levels of abstraction of the AH are depicted by Condenser Efficiency Monitoring Unit (Appendix 4) and Energy Balance (Appendix 6).

Heat conduction/latent heat removal is the process at the generalized function level that realizes these laws. The extent of heat conduction can be estimated by changes in temperature of the contacting objects/masses.

At the physical function level, the objects that facilitate heat conduction are seawater, six seawater pumps, and a multi-chambered condenser. The seawater is pumped through the condenser tubes to remove heat. The condenser contains six sets of identical tubes, each connected to a seawater pump. The WDA identifies five key domain characteristics at this level:

1. Flow rates of the seawater for each set of condenser tubes should be 7.25m^3/s (for each seawater pump is a fix-speed pump)
2. Flow rates of the seawater across each set of condenser tubes should be constant
3. Flow rates of seawater for all six sets of condenser tubes should be the same
4. Temperature of seawater at the same point in each set of condenser tubes should be the same
5. Amount of heat exchange for all six condenser chambers should be the same

The domain characteristics and invariants identified at both generalized function levels and physical function levels of the AH are translated into graphical elements as shown in Figure 9. The seawater monitoring unit depicts 24 variables - the temperatures and volumetric flow rates at the inlets and outlets for six sets of condenser tubes. The numerical values of the inlet and outlet measurements are placed at the bottom and the top, respectively. For each set of condenser tubes, the inlet and outlet data points are mapped as two circles inside a rectangle, which forms the boundary of a temperature (vertical axis) versus volumetric flow rate (horizontal axis) graph (Figure 10). The inlet and outlet data points are also connected with a line. The vertical and horizontal displacements of the line depict differences in temperatures and flow rates, respectively, between the inlet and outlet (Figure 10). The optimal flow rate (i.e. 7.25m^3/s) is set to the horizontal mid-point of the graph/rectangle. Since there are six sets of condenser tubes, there are six graphs placed adjacent to one another.

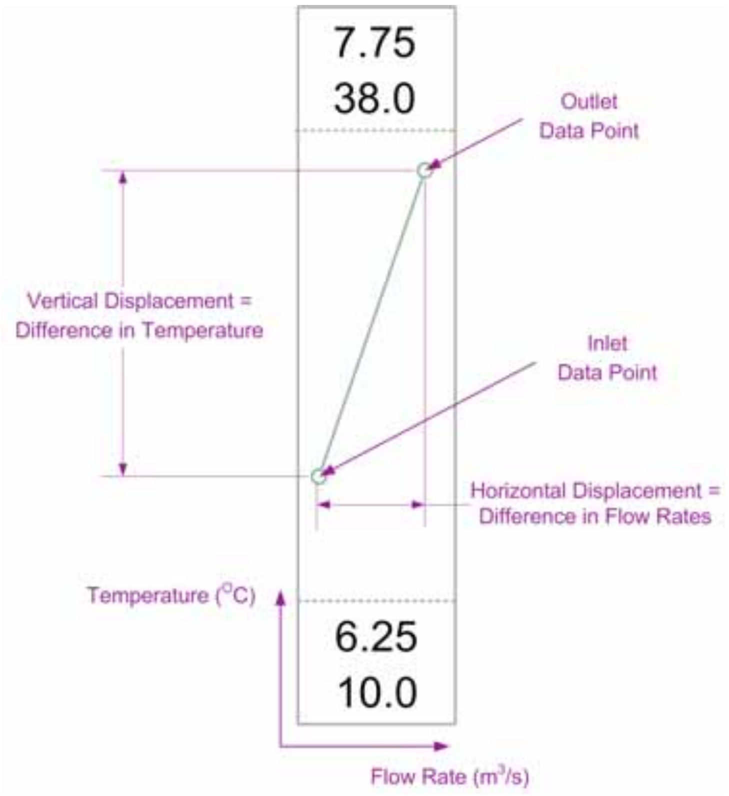


Figure 10: Descriptions of graphical elements for a single set of condenser tubes.

The mapping of 24 variables onto one graphical form reduces the cognitive effort needed to detect violations of the domain invariant. More specifically, operators may monitor at lower levels of cognitive controls (i.e. Skill Based Behaviour and Rule Based Behaviour) with this graphical form than with numerical representations that engage operators at Knowledge Based Behaviour. Thus, detection and diagnosis of anomalies is made easier.

For each condenser tube set, normal operating conditions result in a vertical line located at the horizontal mid-point of the rectangle (i.e. some difference in temperature at the flow rates of 7.25m^3/s between the inlet and outlet). Since the flow rate should be fixed, the length of the line also indicates the amount heat exchange for each set of condenser tubes, illustrating the domain relationship at the generalized function level.

The emergent feature of the graph for each set of condenser tubes is destroyed in different ways as different constraints are violated, allowing operators to detect systems faults/inefficiencies without any numerical computation. If seawater flow rate deviate from the fixed set point (characteristic 1 at the physical function level), the line connecting the inlet and outlet data points appears off-center in the rectangle (Figure 11). If flow rates fluctuate between the inlet and outlet within each condenser tube set (characteristic 2 at the physical function level), the line inside the rectangle would appear slanted as opposed to vertical (Figure 12).

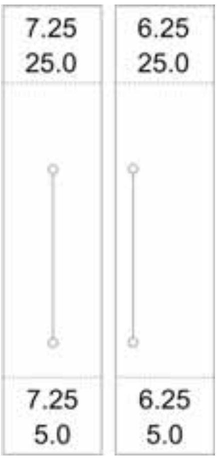


Figure 11: Deviations in flow rates from ideal results in a vertical line that is off-centre (right) as opposed to the centre (left).

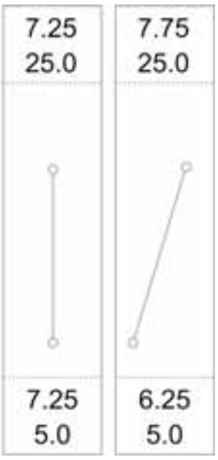


Figure 12: Fluctuation in flow rates across inlet and outlet results in a rotated line (right) and destroys the emergent feature of a vertical line (left).

The individual graphs that depict the six sets of condenser tubes form another emergent feature in conjunction to one another. When all six sets of condenser tubes are operating in normal conditions, this graphical unit also shows six identical vertical lines evenly spaced inside six rectangles (Figure 9) as all condenser tubes should behave in exactly the same manner (characteristic 3, 4, and 5 at the physical function level). Thus, variations between different condenser tubes would be visible without any numerical computation. For instance, when heat exchange differs amongst the condenser tubes (characteristics 5 at the physical function level) because of variance in fouling, the vertical displacement of the lines also varies, as exemplified by the line second from the right in Figure 13. In extreme situations, all condenser tubes may behave differently, suggesting the potential need for plant shutdown due to unstable plant cooling (Figure 14).

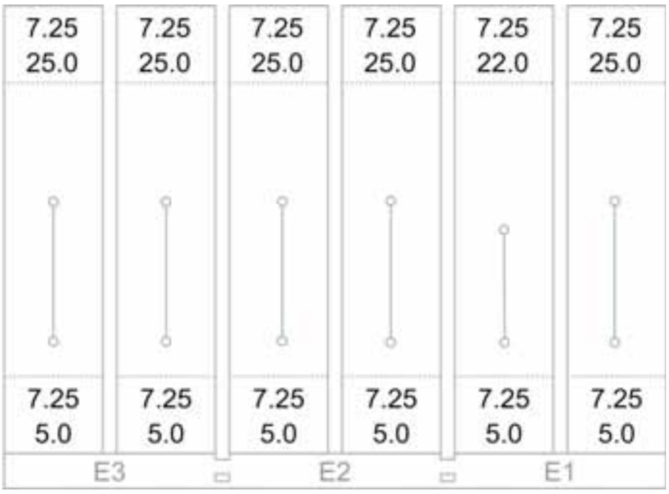


Figure 13: One of the six sets of the condenser tubes (second from the right) deviates from others destroying the emergent feature and isolating the problematic area.

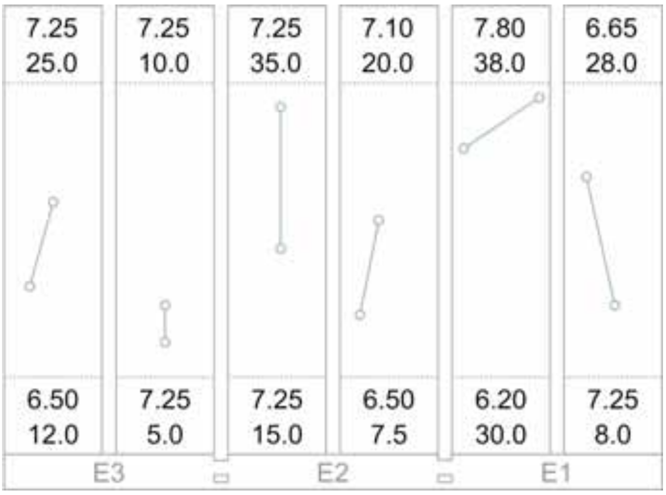


Figure 14: In an extreme situation, the graphical elements in this unit appear chaotic suggesting unstable cooling and plant shutdown.

Appendix 3: Condenser Instrumentation

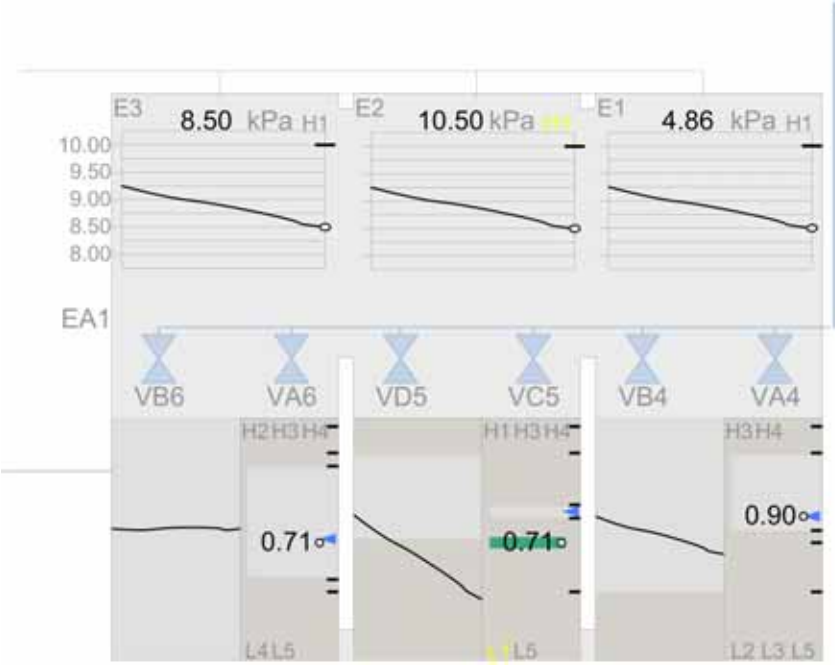


Figure 15: Condenser instrumentation monitoring unit depicting the domain characteristics at the functional purpose and physical function level of the AH.

Figure 15 presents the graphical form for monitoring the instrumentation readings connected to the three-chambered condenser. The pertinent domain information were discovered at the functional purpose and physical function level of the AH model for the Condenser and Vacuum System (461) at the Level 3 part-whole decomposition of the condenser area.

The domain characteristics that are discovered at the functional purpose, abstraction function, and generalized function levels of the AH are described and illustrated in Appendix 4, the condenser efficiency monitoring unit. In brief, the functional purpose of the condenser is to maximize the efficiency of the low-pressure turbines and to satisfy condensate demand of the feedwater area. The means to achieve these purposes are through application of mass, energy, and momentum conservation laws at the abstract function level. The processes that realize these laws are found at the generalized function level. Heat conduction/latent heat removal process can facilitate condensation, creating a vacuum for the turbine area and providing condensate for the feedwater area.

The key equipment at the physical function level that facilitates the processes at the generalized function level is the three-chambered condenser. Each chamber is instrumented with a pressure sensor and a volumetric level sensor that could capture the key characteristics at the functional purpose and physical function levels as follows:

1. The pressure across the three chambers of the condenser should be the same
2. The condensate volume at the hotwells across the three chambers of the condenser should be the same
3. Lower pressure suggests higher low-pressure turbine efficiency
4. Adequate condensate level suggests adequate supplies of condensate for the feedwater area

5. The fluctuation of these measures suggests the stability of the Condenser and Vacuum System (461)

(Note that this display unit should be interpreted in conjunction with Condenser Efficiency Monitoring Unit in Appendix 4.)

The pertinent domain information is mapped onto six trend graphs enclosed by a condenser icon. For each of the three chambers, the numerical readings of the pressure and volume level are presented in conjunction with their trend graphs. For each indicator, the alarm limits are marked with black tick marks on the graphs.

Appendix 4: Condenser Efficiency

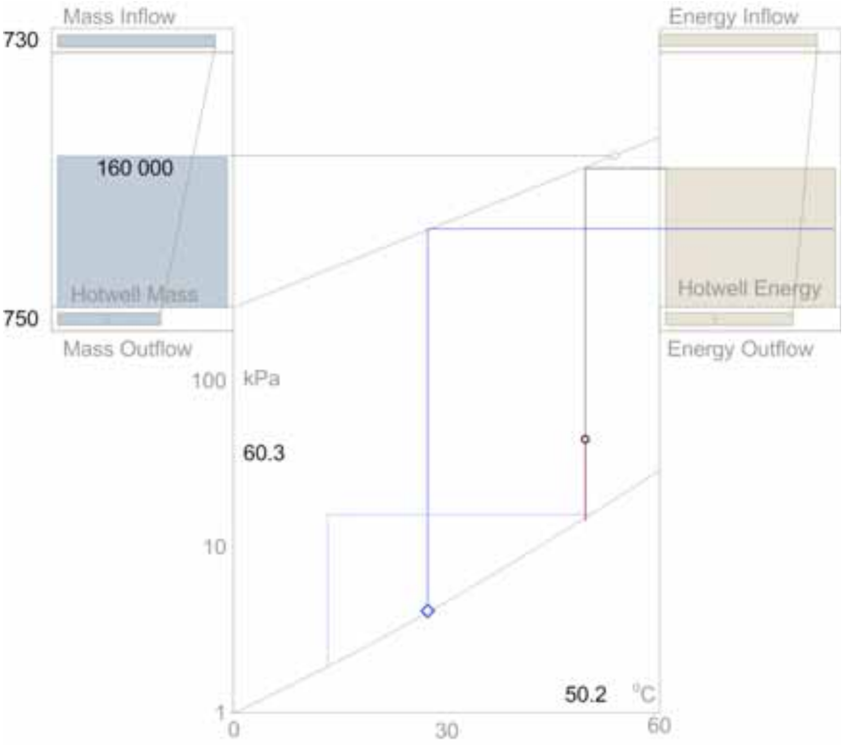


Figure 16. Condenser efficiency monitoring unit, which integrates mass balance, energy balance, and pressure-temperature graph for the condenser.

Figure 16 presents the graphical form for monitoring condenser operations. The pertinent domain information for this form were discovered in the AH model of the Condenser and Vacuum System (461) at Level 3 part-whole decomposition in the condenser area. Figure 17 is a simplified, distilled AH summarizing the pertinent information.

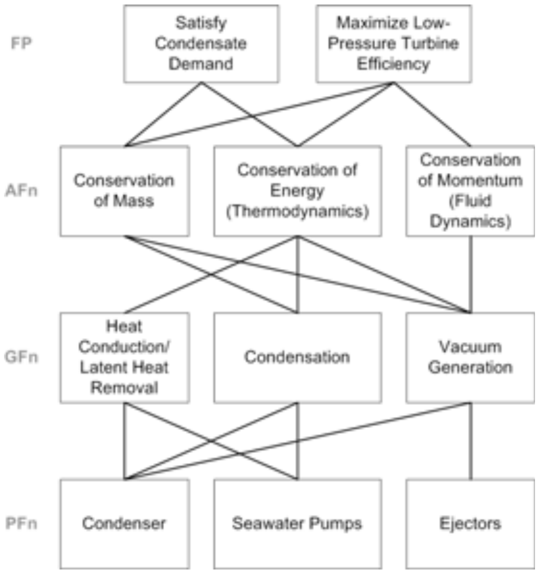


Figure 17: Simplified, distilled, level 3 abstraction hierarchy for the Condenser and Vacuum System (461).

Two relevant functional purposes are to maximize efficiency of the low-pressure turbine and to satisfy condensate demand of the feedwater area. The means to achieve these purposes are through application of mass, energy, and momentum conservation laws at the abstract function level. Turbine efficiency can be optimized by taking advantage of steam momentum across the low-pressure turbines; condensate can be converted through energy transfers. The processes that realize these laws are found at the generalized function level.

The heat conduction/latent heat removal process can lead to condensation, creating a vacuum for the turbine area and providing condensate for the feedwater area. The WDA identifies 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. In addition to this graphical monitoring unit, some information at the physical function level is presented in the condenser instrumentation monitoring unit in Appendix 3. Also see Appendix 2 for the seawater monitoring unit.

A mass balance, energy balance, and pressure-temperature plot are integrated into the interface to convey information specified by the relevant portion of the AH. The mass and energy balances are designed to illustrate the functional purpose and abstract function information (Figure 18).

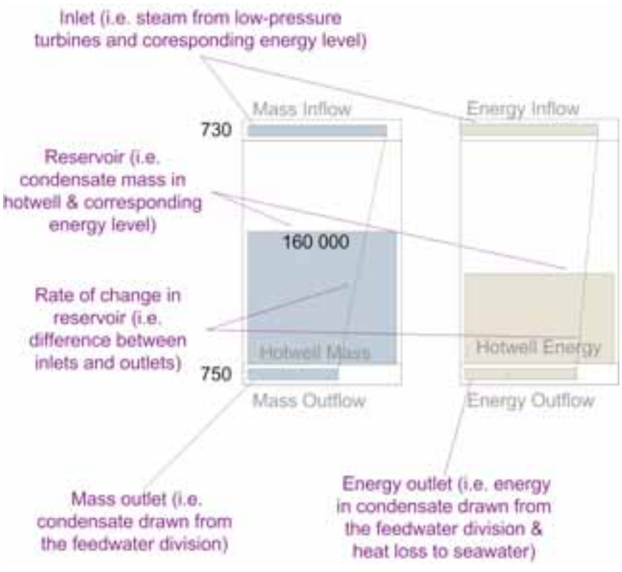


Figure 18: Mass and energy balances the condenser.

The mass balance indicates how well the condenser is satisfying the condensate demand of the feedwater area. The inlet and outlet are represented by the two connected bar graphs at the top and bottom, respectively. The two horizontal bar graphs are also connected with a line to illustrate their difference. The vertical bar graph in the center represents a reservoir. Under steady-state conditions, the mass inlet and outlet should be equal, resulting in a vertical connecting line and a stable mass reservoir (i.e. a condensate supply buffer). 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 constant. Similarly, at a given power level, a lower energy input suggests a higher efficiency.

Figure 17 indicates 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 monitoring unit (Appendix 2). The relevant information about the heat conduction process at the generalized function is linked to the abstract function through another energy balance (Appendix 6).

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 pressure inside the condenser are mapped onto a plot that depicts the condensation and vacuum generation processes (Figure 19). 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 are depicted by projection lines from the circle and blue diamond to the energy balance.

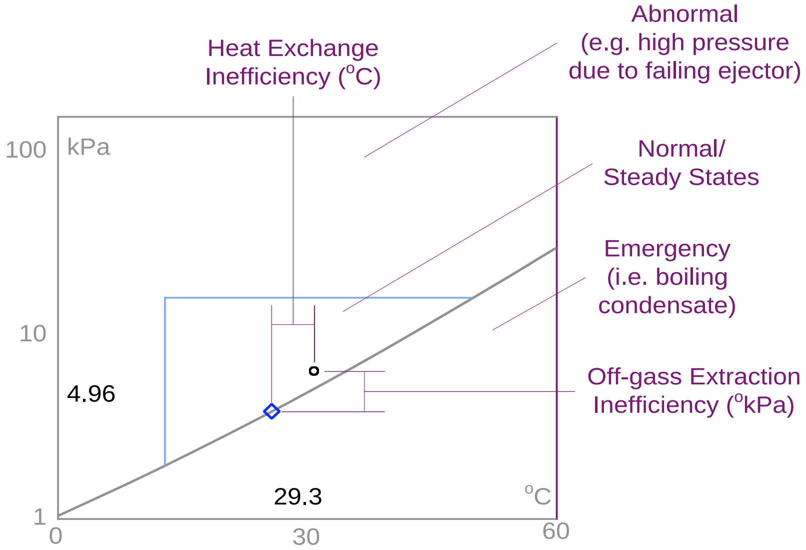


Figure 19: Temperature-pressure graph of the condenser.

This graphical form has several unique characteristics for monitoring condenser operations. The work domain constraints and invariants are mapped onto this graphical form, providing support for problem solving (i.e. knowledge-based behaviour). The identified domain information, such as mass input-output balance and pressure-temperature constraints, is theoretically necessary to detect faults or assess efficiency. Furthermore, this graphical form permits operators to rely on lower level of cognitive controls during monitoring.

The balances depict input-output equilibrium by a connecting line, which is a form of signals or signs (i.e. time-space indicators or familiar percepts) that trigger SBB or RBB as opposed to symbols (e.g. numbers) that activate KBB (e.g. numerical computations). The energy balance also provides an unambiguous indication of system stability of the condensation process in thermodynamic terms. This relieves operators from mental calculations using temperature and mass data.

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. The plot (Figure 19) 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). Operators can monitor the condenser's performance visually, based on the location of the operating point (i.e. white circle).

The projection lines from data points on the plot (i.e. circle and blue diamond) toward the energy balance assist the operator in monitoring tasks by illustrating means-ends relationships between the abstract and generalized functions (Figure 20). 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. As the mass, energy, temperature, and pressure deviate from steady-state conditions, the projection lines form a distinctly different pattern (Figure 21). The features in this graphical form demonstrate that SRK can guide design to convey relevant domain information in such a way that capitalizes on innate human perceptual capabilities.

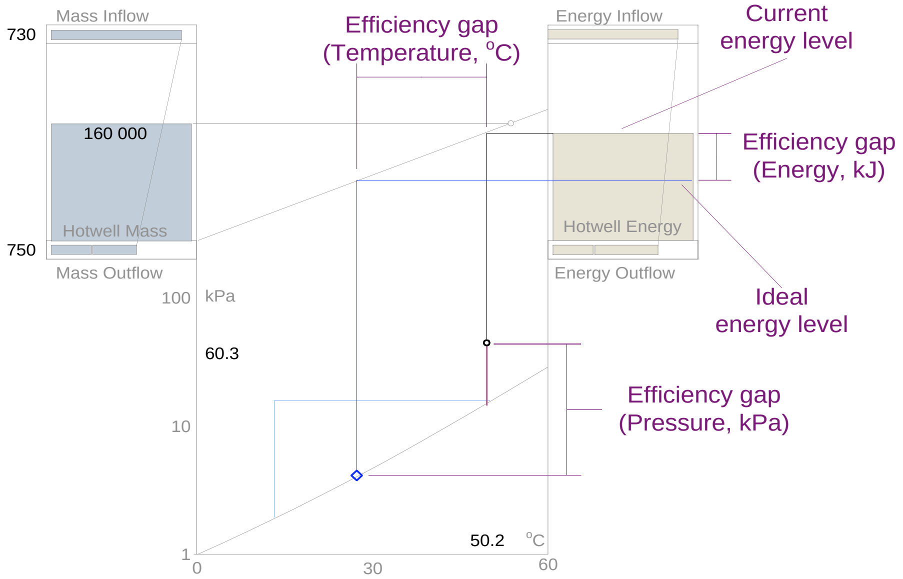
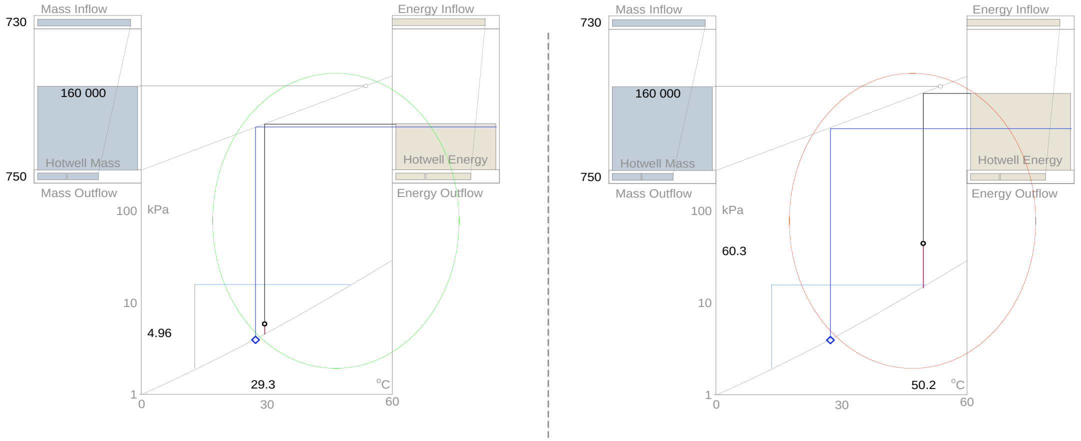


Figure 20: Integrated graphical forms depicting efficiency gaps of the condenser.



(a) Normal

(b) Abnormal

Figure 21: Integrated graphical forms facilitating pattern recognition for monitoring. (a) Normal conditions. (b) Abnormal conditions.

Appendix 5: Re-combiner

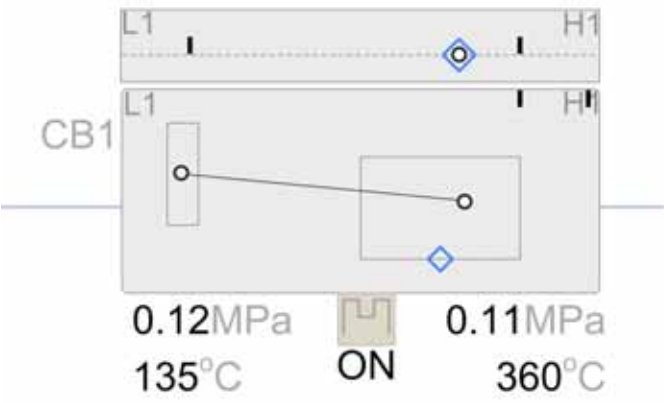


Figure 22: Re-combiner monitoring unit depicting the recombination process of hydrogen and oxygen off-gasses.

Figure 22 presents the graphical form for monitoring the re-combination processes of hydrogen and oxygen off-gases. The pertinent domain information for this graphical form was discovered in the AH model at Level 3 part-whole decomposition for the Off-gas Re-combiner System (348) in the condenser area.

The functional purposes of the re-combiners are to minimize hydrogen content of off-gas and to maximize conversion of non-condensable gases into condensable gases. The means to achieve these functional purposes are energy conversion and mass transformation. Based on chemistry and physics, the mass content can be transformed through energy states changes. The processes that realize the energy conversion and mass transformation are heating and chemical reactions at the generalized function level. Heating provides the activation energy necessary for the chemical reaction to occur. The chemical reaction is the recombination of hydrogen and oxygen (See Equation 1). Pd is the catalyst and the reaction is exothermic (i.e. energy is released from the reaction).

$$2H_2 + O_2 + Pd = H_2O + Pd \quad (1)$$

At the physical function level, heaters and re-combiner tanks are the means to the heating and re-combination processes, respectively. The WDA identifies the following characteristics the generalized and physical function levels:

1. The operating range of the inlet temperature is between 130-150°C
2. The operating range of the inlet pressure is between 0.11-0.14MPa
3. The operating range of the outlet temperature is between 130-395°C
4. The operating range of the outlet pressure is between 0.10-0.13MPa
5. The expected inlet temperature and pressure are 140°C
6. The expected outlet temperature and pressure are 300°C, 0.1MPa
7. The operating range of re-combiner tank temperature is between 130-400 °C
8. The expected temperature of the re-combiner tank is 350°C

The WDA also identifies other domain characteristics; however, they are not depicted in the ecological interface due to instrumentation limitation. Specifically, the flow rate of hydrogen and oxygen at both inlet and outlet are not presented. Hydrogen and oxygen concentrations would be the ideal indicators for the interface to illustrate both functional purpose and generalized function information, but they are neither available at the power plant nor in HAMBO. Nevertheless, the temperature and pressure parameters should provide sufficient indication of the operating conditions (see below).

Figure 1 primarily depicts the domain information at the generalized and physical function levels and indirectly illustrates the functional purpose. The large rectangular box represents the re-combiner tank superimposed onto a pressure-temperature plot (see Figure 23). The pressure-temperature plot contains two white circles, which represent the pressure-temperature values at the inlet (left) and outlet (right) of the re-combiner tank. The corresponding numerical values are presented below the re-combiner tank graphic. The rectangles inside the plot mark the operating ranges/constraints for the inlet (left) and outlet (right) of the temperature and pressure values. The meter above the re-combiner tank depicts the tank temperature (white circle). Below the re-combiner tank is a heater, which provides the activation energy for facilitating the chemical reaction as necessary. The functional purpose is indirectly illustrated by the line connecting the inlet and outlet pressure-temperature data points. Given that recombination is an exothermic reaction that produces less moles of molecules than the reactants, temperature increase and pressure decrease from the inlet to outlet are expected. Thus, the line connecting the inlet and outlet data would provide adequate inference for the level at which recombination is occurring or the degree to which the functional purposes are being satisfied.

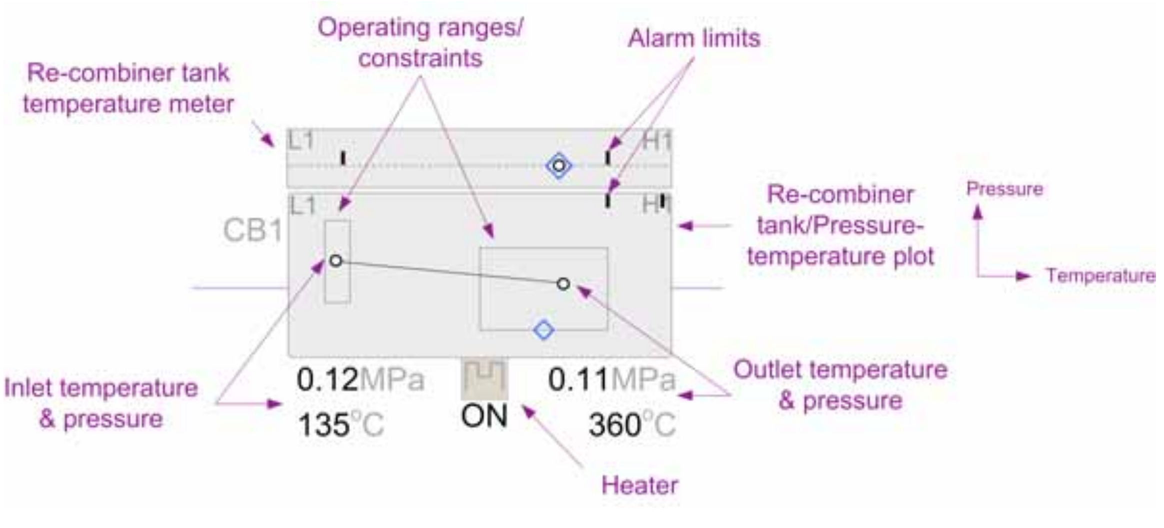


Figure 23: Description of the re-combiner monitoring unit.

This graphical element supports the lower levels of cognitive control (i.e. SBB and RBB) in monitoring the re-combination system, thereby increasing cognitive efficiency. Given that the temperature and pressure at the inlet and outlet of the re-combiners are presented in conjunction with the operating ranges and alarm limits graphically, operators can assess stability of operating conditions by visual inspection of the distances between the data points to the operating limits. This form of monitoring is more cognitively efficient than numerical comparisons between operating states and limits based on memory (KBB). Similarly, the length of the connecting line between the inlet and outlet data points permits operators to assess the effectiveness of the re-combiners visually. Furthermore, by presenting the functional purpose information (i.e. the connecting line between the inlet and outlet data points) and the operating/alarm limits, the relationship between the violation of domain constraints and functional purpose become explicit. For instance, a short connecting line as a result of temperature falling below the operating limit at the outlet implies reduced chemical reaction rate, and thus, explosion hazard downstream due to high hydrogen concentration. On the other hand, a long connecting line as a result of temperature exceeding beyond the operating limit at the outlet implies excessive chemical reaction rate, and thus, explosion hazard of the tank due to uncontrolled exothermic reactions.

Appendix 6: Latent Heat Transfer

Figure 24: Energy Balance depicting the energy relationship between coolant heat loss and seawater heat gain.

Figure 24 presents the graphical form for monitoring the instantaneous relationship between the heat loss from coolant and the heat gain to seawater. The pertinent domain information for this form were discovered in the AH model at Level 2 part-whole decomposition in the condenser area. In particular, this graphical form depicts parts of the abstract function level.

The relevant functional purposes of the condenser area are to satisfy condensate demand of the feedwater area and to provide adequate cooling to the power plant (via condenser). The means to achieve these two purposes is energy transfer at the abstract function level. Based on the laws of thermodynamics, the higher energy mass transfers energy to the lower one, and energy changes between the masses must be balanced (i.e., sum to zero). The process that realizes the energy transfer is latent heat removal/heat conduction; and the objects participating in the heat conduction are the coolant, seawater, seawater pumps, and the condenser. Figure 24, as mentioned, depicts information at the abstract function level. The bar at the left represents the heat loss from coolant (i.e., the higher energy mass) and the right bar represents heat gained by seawater (i.e. the lower energy mass). The line connecting the two bar graphs forms an emergent feature that conveys the balance between these energy levels. The functional purpose information is depicted by the Condenser Efficiency Monitoring Unit (Appendix 4), while the generalized function and the physical function levels are illustrated by both Appendix 4 and Appendix 2.

The benefits of the energy balance graphical element for monitoring are threefold. First, it provides an unambiguous indicator of the stability of the condensation process in thermodynamic terms as compared to single parameter representations, which must be interpreted in conjunction with other parameters (e.g. mass and temperature). This relieves the operators of the arithmetic processing involved in integrating several variables, an example of Knowledge Based Behaviour – which is effortful and error-prone. Second, the energy balance differentiates normal (balanced) from abnormal (imbalanced) states of the process in a salient manner, thereby facilitating early detection of deviations from expected conditions. Third, the energy balance can indicate changes in heat transfer efficiency. A *temporary* energy imbalance depicts a transient state of the plant that typically affects cooling and efficiency. For instance, if seawater temperature increases, resulting in a decrease in heat transfer efficiency, the bar graph representing the energy gained by the seawater will decrease first, resulting in an energy imbalance (Figure 25). On other hand, if the temperature of the exhaust steam from the turbine increases, the reverse occurs.

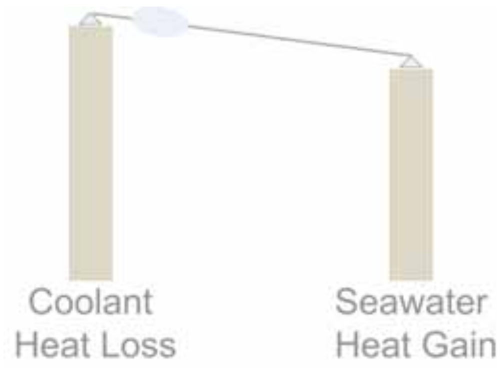


Figure 25: An imbalance between heat gain and loss denoting violation of domain constraints.

Appendix 7: Mass balance

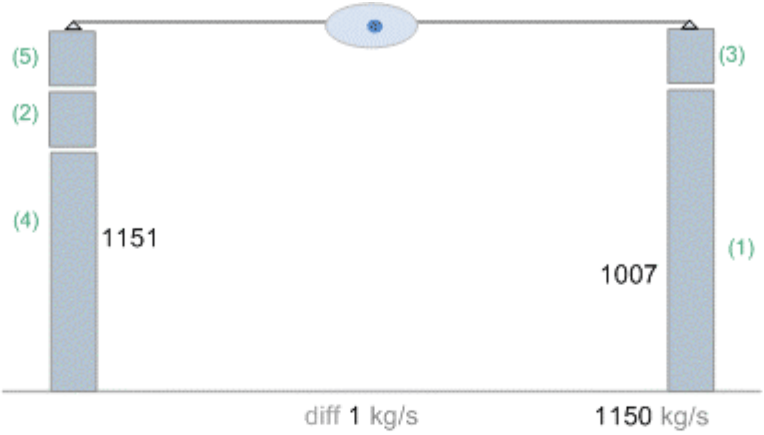


Figure 26: Graphical unit depicting mass balance over control volume.

The “Mass balance” graphical unit shows the state of the individual flows, the total flows and the relationship between the total flows entering and leaving a control volume.

Functionality and appearance

The graphical unit consists of two “bar graph” elements that each represents the values of mass flows entering or leaving a control volume. The bars representing entering flows are stacked on top of each other and the bars representing leaving flows are stacked on top of each other. The height of each of the two resulting pillars then represent the total value of flows entering and leaving.

The top of the two pillars are connected by a line to support easy comparison of the total flows entering and leaving the control volume. If the flows are equal, the line will be perfectly horizontal. If the values are not equal, the line will be slanted. This is a powerful way of visualizing inequalities as even a slightly slanted line is easily distinguishable from a completely horizontal one.

Figure 27: Mass balance with horizontal line

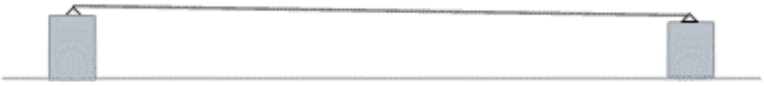


Figure 28: Mass balance with slanted line

A common problem with this basic mass balance display is that it is difficult to find a size and resolution that allows the graphical unit to appear with appropriate visual salience in cases where there is a very large difference as well as when the difference is very small (yet significant). To address this, an oval containing a small circle has been added to the mass balance graphical unit (see Figures 29, 30 and 31). This functions in the way that, even for small differences between the pillar lengths, the small circle moves towards the tallest pillar (similarly to a bubble carpenter's level). When the small circle reaches the side of the oval it should be possible to directly see that the line between the two pillars is no longer horizontal.

Figure 29: Small circle is closer to the leaving flow bar, indicating that slightly more flow is leaving the control volume

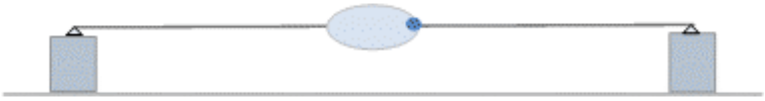


Figure 30: Small circle is at the right hand side of the oval and the line is now slightly skewed

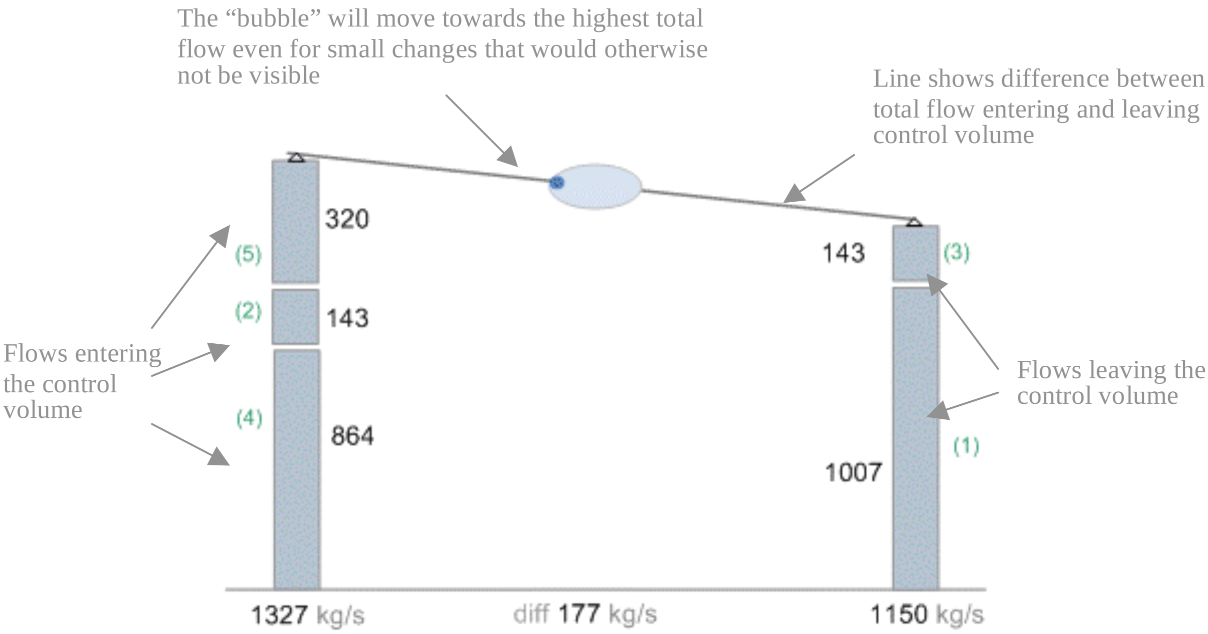


Figure 31: Mass balance during non-steady state condition

Interpretation of the unit:

Under steady state process situations the total value of the flows entering a control volume should equal the total value of the flows leaving a control volume. If these values are not equal during steady state process situations this means there is a disruption somewhere in the system. The interpretation of this unit depends on the characteristics of the actual control volume for which it is used:

Case 1: Mass accumulation is not possible in the control volume (no tanks or compressible liquid): The two flows should always be equal; a sloped line indicates a leakage.

Case 2: Accumulation of mass is possible: The steady state is indicated by perfectly balanced in and out flows. An imbalance reflects the rate of accumulation derived from the flows, which may be compared for instance to measures of accumulation derived from tank levels.

In order to use this display unit it is also required to know the location of the different measurement points that are added and compared to see how they define a control volume with an expected behaviour. For the condensate and feedwater displays, a filled background area and special green number labels have been added to the process mimic part of the display to clearly define the control volume and provide cross-referencing between the mass balance and process mimic representations of the different mass flow measurements (see Figure 32). In the turbine displays the mass balances are placed directly in the process mimic part of the displays.

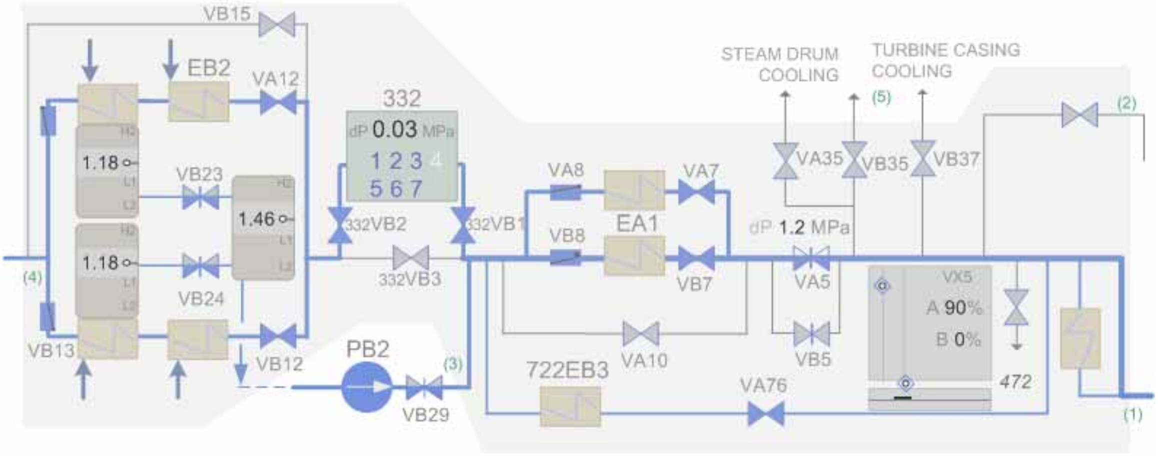


Figure 32: Visualization of control volume

Appendix 8: Condensate pumps monitoring

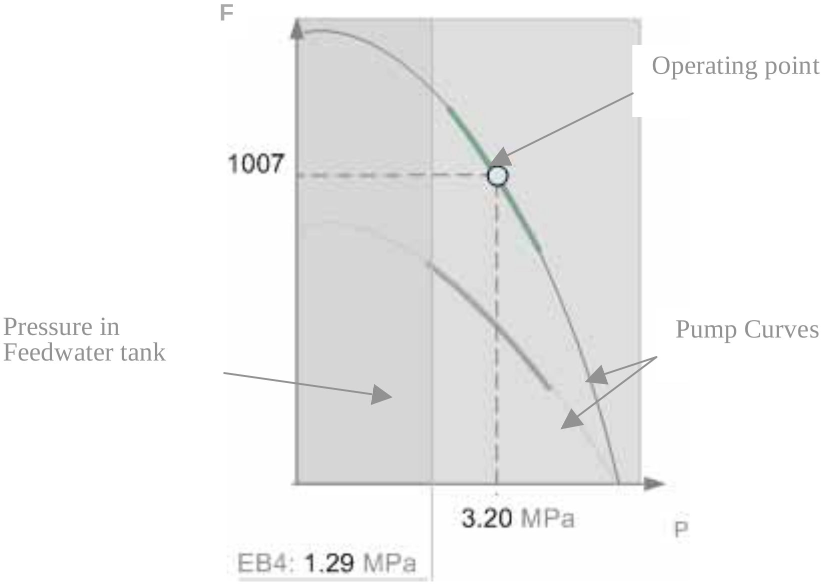


Figure 33: Graphical unit depicting the condensate pumps.

The Condensate pumps graphical unit visualizes the pressure and flow after the condensate pumps and puts them in context with a pump curve. The sensor that measures flow and pressure values is placed after the flows from the pumps have been combined, so the visualization shows the combined flow and average pressure out of the active pumps, therefore the pump curve is also a combined curve for all active pumps (see Figure 33).

The graphical unit consists of a graph with flow along the y-axis and pressure along the x-axis. The graph contains a small circle that represents the combined operation point for the active pumps. Also shown are two pump curves, one representing the area the operating point is expected to be in when two pumps are active and the other representing the area when only one is active. The pump curve that represents the non-active state is faded out. All three pumps are never continuously active under normal operation. The graphical unit also contains an area that is filled with a darker grey colour than the main area and is also separated from the main area by a line. This line indicates the pressure in the Feedwater tank which is located downstream from the condensate pumps. The reason for visualizing this is that one of the functions of the pumps is to increase the fluid pressure to above the pressure within the Feedwater tank. The operation point should therefore be to the right of this line.

In traditional pump diagrams, pressure is shown along the y-axis and flow along the x-axis. The reason for this being inverted in this graphical unit is that the pump diagram is connected to a Mass balance graphical unit.

Since the combined flow from the condensate pumps equals one of the flows entering the Mass balance control volume, the graphical units are designed so that the height of one of the mass balance bars equals the flow of the current operating point. This allows users to see how the flow from the condensate pumps affects the mass balance downstream (see Figure 34).

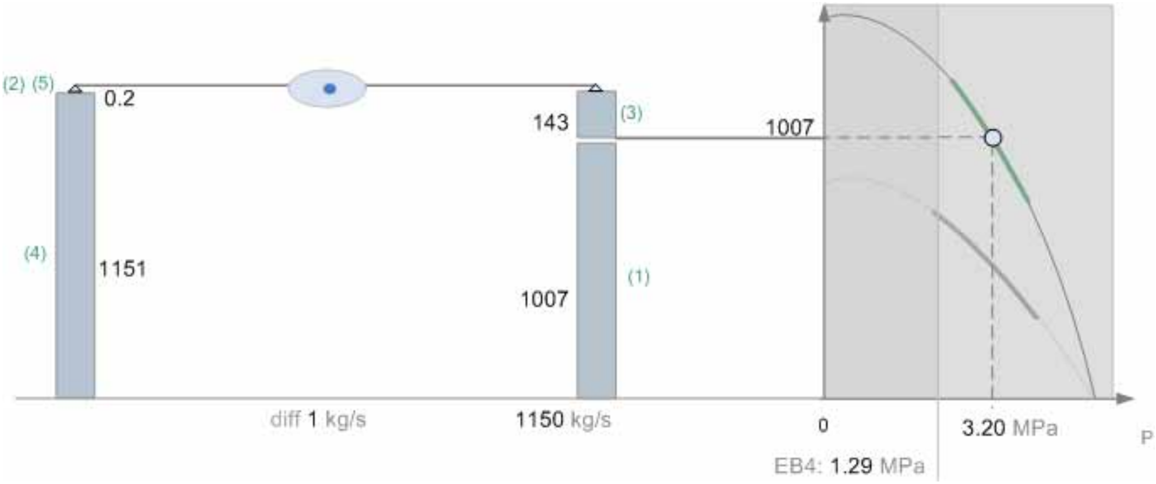


Figure 34: Y-axis of Condensate pump graphical unit connected to Mass balance graphical unit.

Appendix 9: Condensate tank

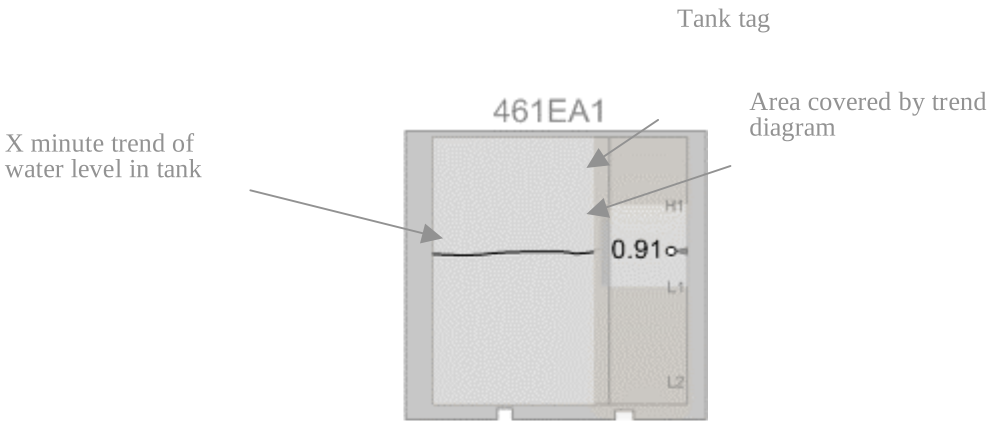


Figure 35: Graphical unit depicting the condensate tank

The condensate tank graphical unit visualizes the water level in the tank (Figure 35). It is visualized both as a trend to the left (time represented on the x-axis and level represented on the y-axis) and in relation to the actual physical height of the tank on the right. The y-axis does not cover the entire height of the tank since this would make it difficult to observe small changes. Therefore the diagram itself moves along the height of the tank. The area of the tank the diagram covers can be seen from the dark grey rectangle between the trend diagram and the right side of the tank where the entire height of the tank is visualized. This rectangle moves vertically along the diagram on the right side and represents the area the trend diagram currently is covering

In addition to showing the entire height of the tank, the right hand side of the unit also shows the current value, set point and alarm limits (Figure 36). The current value is shown both numerically and as a white circle. Both indicate the level by moving vertically across the diagram.

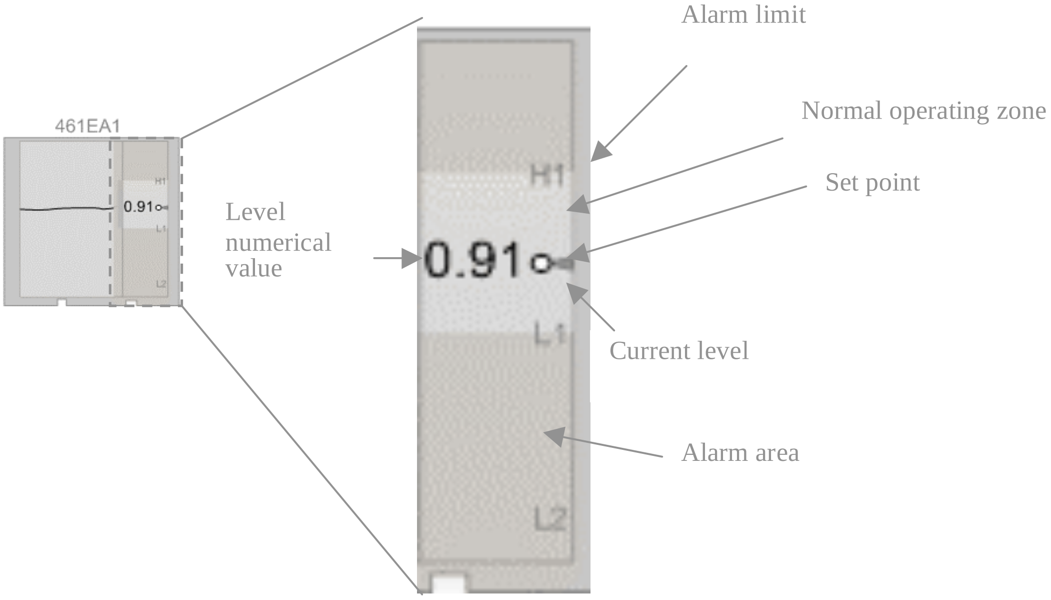


Figure 36: Right hand side of graphical unit

Appendix 10: Valve information unit

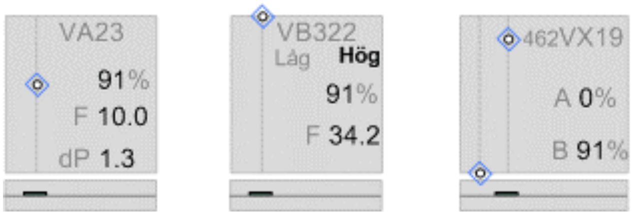


Figure 37: Example of graphical unit depicting special valve information

The “Valve info” graphical units give the user information on valve opening, expected valve opening and other information important to understanding the function of the valve (Figure 37).

Functionality and appearance

The graphical unit consists of one or more vertical axis which represents the position of the valve or valves (from 0% to fully open). The actual valve position is shown as a white dot moving along the axis and the expected valve position for the current reactor effect is shown by the superimposed blue diamond symbol. The actual valve positions are also shown numerically to the right of the axes. Beneath the axes there is a green bar graph representing the difference between controller output and actual valve position for each valve. The bar-graphs will generally not be seen during fault-free operation, while a stuck valve or similar fault condition will leave a visually salient indication of the discrepancy.

Additional information that through the WDA has been considered valuable to the user in understanding how the valve or valves are functioning are also included in the graphical unit. This information can be pressure drop over the valve, flow, etc.

Appendix 11: Temperature profile

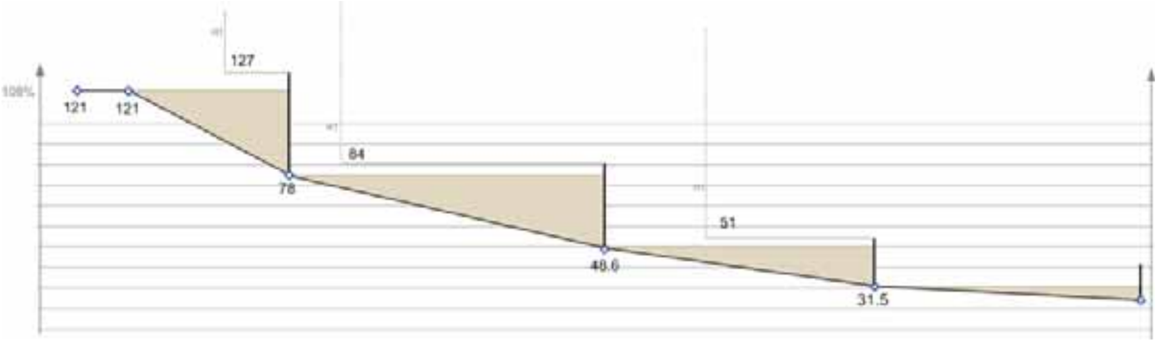


Figure 38: Graphical unit depicting the temperature profile of the main condensate system

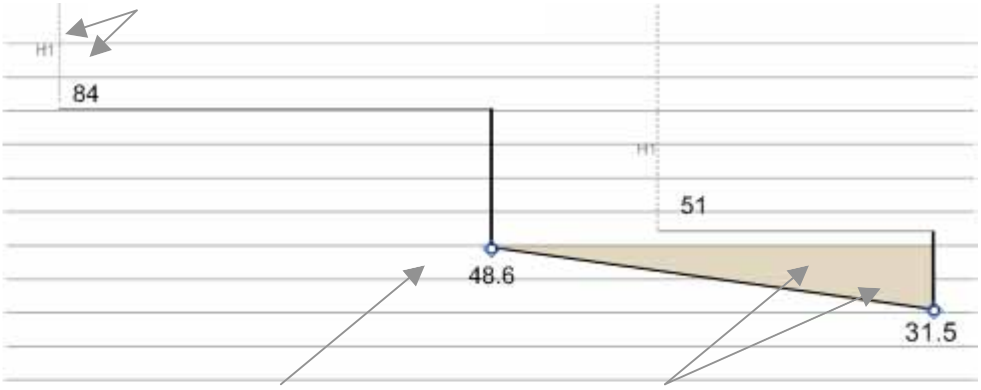
The “Temperature profile” graphical unit shows how the temperature of the main condensate flow develops along the system and the relationship between this temperature and the bleed streams from the turbines that the main flow are heat exchanged with (Figure 38).

Functionality and appearance

The graphical unit consists of a graph with temperature along the y-axis and physical location within the process system along the x-axis. Along the x-axis, from right to left, the temperature of the main condensate flow can be followed at different points in the process. These points are located after heat exchangers, so therefore it is possible to use this unit to assess the heat exchange function of the system. It is possible to see where these points are located within the system as their horizontal position corresponds with the position of the process which is visualized directly above the profile.

Also visualized are the temperatures of the bleed streams from the turbines that the main flow is heat exchanged with. These are shown as greyed out lines that connect with the temperature profile of the main flow. The coloured areas show the temperature difference of the main condensate flow before and after heat exchanging.

Bleed stream and temperature of bleed stream being heat exchanged with main flow



Temperature of main fluid before heat exchange

Top of coloured area shows temperature difference of the main flow before and after heat exchanging. The vertical line allows user to compare the temperature before heat exchanging, after heat exchanging and bleed stream temperature

Figure 39. Temperature profile

Interpretation of the unit:

Under steady state process situations the temperature profile for the process is related to the reactor effect. This means that an unfamiliar or changing temperature diagram under a constant reactor effect means that there is a disruption that has either effected the:

- temperature of the main flow going into the system
- heat exchange function

These are easily distinguishable from each other since the former causes a change in the temperature before there has been any heat exchange. If the heat exchange function has been affected, it can be assessed from the unit whether this is due to the temperature of the bleed streams. Other conditions that could affect the heat exchange function can also be deduced indirectly from the unit.

Appendix 12: Feedwater pumps

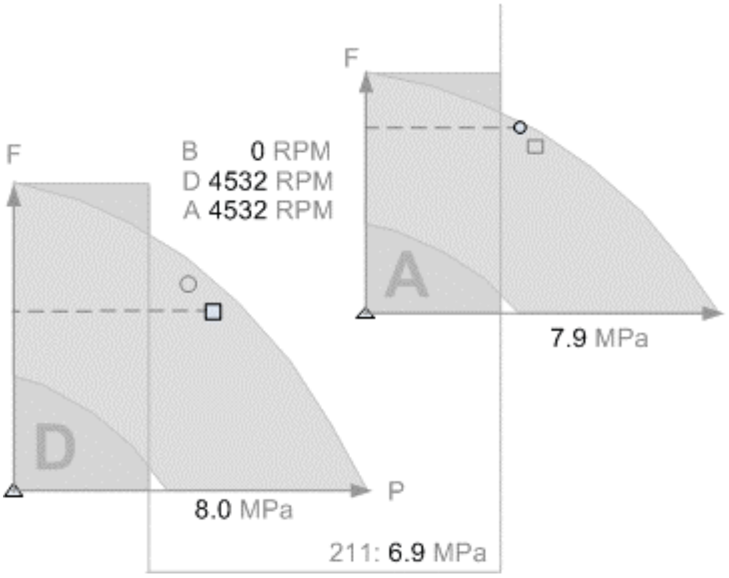


Figure 40: Graphical unit depicting two feedwater pumps

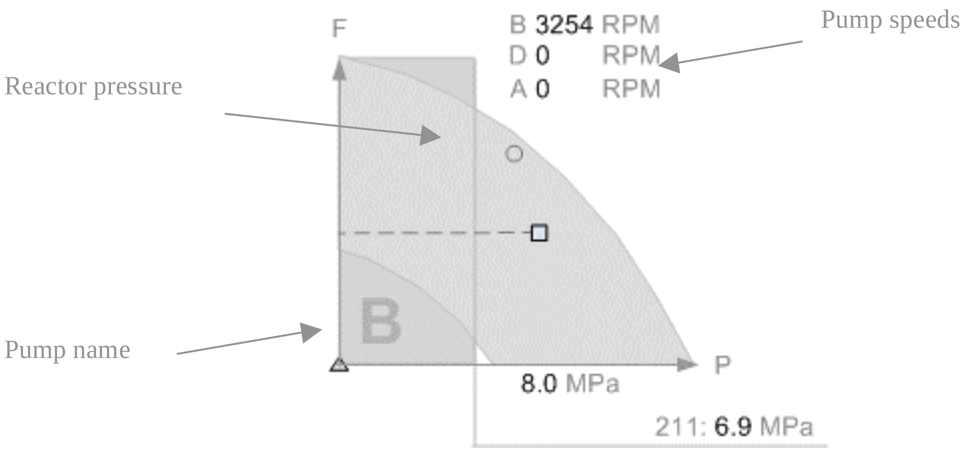


Figure 41: Graphical unit depicting a single operating feedwater pump

The graphical unit represents the variable speed feedwater pumps, which are used to transport fluid from the feedwater tank to the reactor. There are three feedwater pumps, but only one or two are active at a time. The unit visualizes the pressure and flow (with pressure along the x axis and flow along the y axis) after one or two feedwater pumps, depending on how many are active, and puts them in context with pump curve (Figure 40 and 41). Since the pumps are variable speed, the pumps curves that are visualized are the ones at maximum speed and minimum speed. Since there are flow sensors just downstream of each individual feedwater pump, it is possible to visualize the pumps separately and not as a combined pump diagram as it was done with the condensate pumps.

The area in between has been coloured light grey to indicate a normal operating envelope. The current pressure and flow is visualized either as a grey circle or square. In addition each pump curve contains a vertical line that represents reactor pressure. The reason for visualizing this is that one of the functions of the pumps is to increase the fluid pressure to above the pressure in the reactor. The operation points should therefore be to the right of these lines. Rotational speed for the pumps is also given as rotations per second.

In traditional pump diagrams, pressure is shown along the y-axis and flow along the x-axis. The reason for this being inverted in this graphical unit is that the pump diagram is connected to a Mass balance graphical unit.

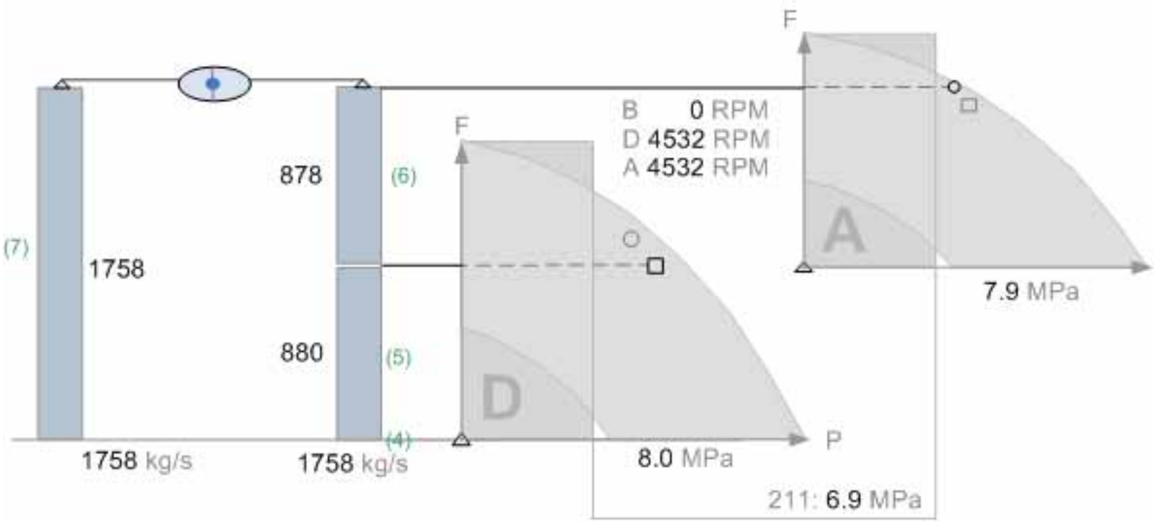


Figure 42: Feedwater pump graphical units connected to mass balance

Since there are flow sensors just downstream of each feedwater pump that can be used directly to show input streams in a mass balance of the feedwater system, these graphical units can be connected, and since each pump has an individual flow sensor, it is possible to connect each pump flow diagram with a mass balance bar (Figure 42). Notice, that the input flow bars are situated on top of each other and therefore the feedwater pump units can not have the same vertical position. The y-axis of one of the feedwater pumps has to begin at the y-axis value of the operating point of the other feedwater pump. In the case shown in Figure 3, the flow of feedwater pump D corresponds to input flow (5) in the mass balance and the flow of feedwater pump A corresponds to input flow (6) in the mass balance. If the flow of feedwater pump D should increase, the whole of the feedwater pump A sub-unit would move upwards.

Appendix 13: Flow balance

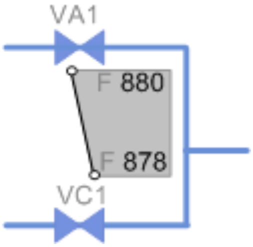


Figure 43: Graphical unit depicting flow balance.

The “Flow balance” graphical units show the flows and relationship between the flows of two parallel pipelines.

Functionality and appearance

The graphical unit consists of two dots that move along separate invisible horizontal axes. The axes represent the flow in the respective pipelines, with a low flow being to the right and a large flow being to the left. The two dots are connected by a line supporting easy comparison of the flows. If the flows are equal, the line will be vertical. If the values are not equal, the line will be slanted (Figure 43). In addition, the area to the right of the line is coloured grey. This makes it even easier two observe whether the two flows are equal or not.

Interpretation of the unit

During normal operation the flow in the parallel pipes should be equal. If they are not equal, this usually indicates either a leakage in one of the pipes, resulting in a lower flow if it is before the transmitter or higher flow if it is after, an obstruction in one of the pipes, resulting in a lower flow in that pipe or an internal leakage in one of the valves, resulting in a higher flow in that pipeline.

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• John R. Hajdukiewicz & Kim J. Vicente

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CEL 07-02	"The Ecological Interface Design experiment (2005) (HWR-833)" • Gyrd Skraaning, Nathan Lau, Robin Welch, Christer Nihlwing, Gisle Andresen, Liv Hanne Brevig, Øystein Veland, Greg A. Jamieson, Catherine M. Burns