HYDRO SCHEME CONTROL IN A DEREGULATED ENVIRONMENT: COGNITIVE WORK MODELS AND DESIGN IMPLICATIONS

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Most studies of the human supervisor in the power industry have focused on how the reactor operator monitors the energy source and the containment of radiation and controls thermodynamic cycles, while serving base electricity loads. In contrast, the human supervisor of hydroelectric generation in a dynamic, deregulated, market environment, where control activity is motivated increasingly by market forces, has a surprisingly different role. Our goal in this paper is to note the particularly challenging features of the hydro power plant controller's world, particularly when dealing with a multi-site, multi-storage facility, with complex hydraulic arrangements, large generating units, and a focus on serving peak rather than base loads. We present results of cognitive work analyses that are informing investigations into more effective interface design for hydro scheme control and note challenges in formulating a framework for design.

Introduction

Most studies of the human supervisor in the power industry have focused on the highly regulated US nuclear industry (Moray, 1988; 1997; Roth & O'Hara, 2002) or European equivalents. In such cases the focus has been on how the reactor operator monitors the energy source, the containment of radiation, and the control of thermodynamic cycles, while serving base electricity loads. In contrast, the human supervisor of hydroelectric generation in a dynamic, deregulated, market environment where control activity is motivated increasingly by market forces (NEMMCO, 1997) has a surprisingly different role. This is particularly the case in any hydro generator that is a multi-site, multi-storage facility, with complex hydraulic arrangements, large generating units, and a focus on serving peak rather than base loads.

Our goal in this paper is to note the particularly challenging features of the hydro power plant controller's world and to present results of cognitive work analyses that will inform investigations into more effective interface design for hydro scheme control. We indicate challenges with building an adequate work domain analysis for a system that consists of interlocking domains with very different characteristics. Finally, we note where participatory design is emerging in one particular hydro scheme control context and where it can be effective, before briefly outlining current and future plans and activities.

The human operator in hydro scheme control

The role of the human controller in hydro power plant or hydro scheme control differs in many ways from that of the "human supervisor" in nuclear or fossil power generation (Sheridan, 1997). Many more monitoring and control functions are the responsibility of a single controller, including responsibility for control of the energy source, generation, dispatch, and response to changing market conditions. The extremely demanding nature of the hydro scheme controller's role has emerged forcefully in Australia with the recent privatisation of the traditional government-owned electricity industry. A competitive National Electricity Market (NEM) went into operation in December 1998. The National Electricity Market Management Company (NEMMCO) operates a power pool where electricity sellers (generators) and buyers (customers) trade in a free market. The market is rapidly evolving with new electrical services beyond active power, such as network frequency and voltage control (ancillary services).

Under the new market arrangements NEMMCO has a greater degree of control over individual generators' plant. To enable this, all electricity generators wishing to trade in the market have installed additional IT and invested in operations research to help optimise their use of resources while maximising revenue. Such innovations are sometimes clumsy and can increase human controller workload and jeopardise effectiveness. As an experienced industry control room operator commented of new windows-based control room technology: "it's just an *IT* system, not a *control* system!"

To date, although many studies of non-nuclear power plant control rooms and national grid control centres have been performed (see for example many papers in the UK-based People in Control conference series; 1999, 2001, and Noyes & Bransby, 2001) no coherent design philosophy has been put forward for coupling human hydro scheme controllers with the demands of a dynamic deregulated electricity market. The purpose of our research is to investigate the extent to which advanced functional interface design approaches such as ecological interface design (EID) might help (Vicente & Rasmussen, 1990; Vicente, 2002).

Cognitive work modeling

In order to explore how advanced functional displays could be developed for hydro scheme controllers we turned to cognitive work analysis (Vicente, 1999; Sanderson 2003) and methods for analysing cognitive tasks (Schraagen, Chipman & Shalin, 2000). With these forms of analysis we developed preliminary models of the work domain within which hydro scheme controllers are working and the control tasks they must coordinate throughout the day. Some examples are given here.

Control tasks. Figure 1 was developed from a series of interviews with hydro scheme controllers early in our project, following a modified version of the Critical Decision Method (Hoffman, Crandall, et al, 1998; Wong, 2000, 2002; Wong & Blandford, 2002). The figure presents in prototypical form the monitoring task that hydro scheme controllers perform. The figure indicates that when controllers notice a status alert or a deviation from what they expect to see, they gather information that will help them decide upon a course of action. They gather information in order to better assess the significance of the alert for the market, for electricity generation, and for hydro management, and then to take action if needed. (With some small adjustments the diagram in Figure 1 could be represented as a decision ladder: Rasmussen et al., 1994. We have left it as is to better represent the need to consider market, generation, and hydro management together.)

Through a thematic analysis of critical incidents faced by the controllers, a number of challenges emerged that indicated priorities for information design (Wong, 2002). First, controllers faced difficulties in deriving a picture of the situation. Second, interruptions, simultaneous activities and lagged responses to previous activities were common (see also Figure 2). Third, it was difficult for controllers to maintain good situation awareness between each other and with the processes they are controlling. These challenges were partly due to high information access cost, the presence of too much unstructured or irrelevant data (eg, alarm "showers"), the presence of inadequately diagnostic information, and the compartmentalisation of information that the controller needed to integrate.

Activity analysis. To fully understand the cognitive work of the hydro scheme operator, we also need to see how work demands change and are coordinated through the day. Figure 2 is an activity analysis (Rasmussen et al., 1994) that represents a prototypical summer profile. When hydro generators serve peak rather than base load they will be very sensitive to diurnal changes in electricity demand caused by changing weather or by community occupational and domestic patterns. The figure shows water management, generation, and market conditions as the central rows, but they are surrounded by other sources of distraction and interrupts during the major epochs of the working day, some of which are planned and others unexpected. Arrows in the table show periods over which a situation requiring control of a certain kind is most likely to occur.

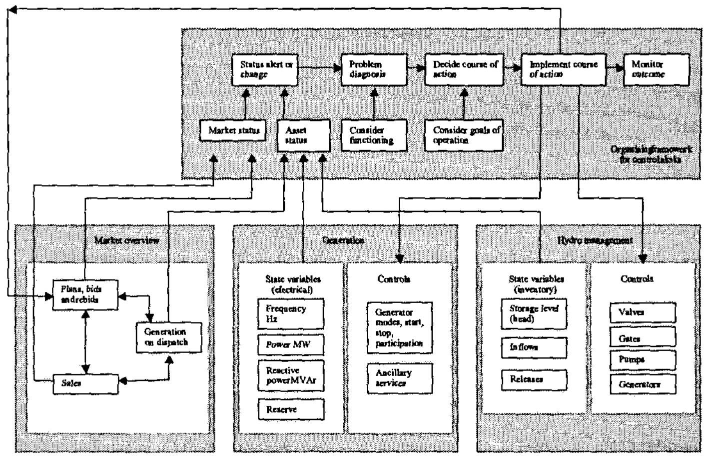

Figure 1: Control task analysis of the hydro scheme controller's monitoring strategy.

The activity analysis in Figure 2 therefore reveals the constraints underlying work tempo. The same analysis has been used to cross-check the requirements for of hydro scheme control room facility redesign. Similar representations have been used in air defence contexts, where we have dubbed them temporal coordination control task analyses (Sanderson & Naikar, 2000; Crone, Sanderson, & Naikar, 2003). While managing a series of other activity threads, the hydro scheme controller is thinking forward in time: ensuring that plant is ready to generate when dispatched, that generation reserve is protected, and that options are open if the unexpected happens (Hollnagel, 2002).

Work domain analysis. The activity analysis does not show the values hydro scheme controllers will use to make decisions or resolve conflicts or fundamental principles of operation. Figure 3 shows part of an analysis of a simple initial work domain of hydro scheme control that reveals such values (Rasmussen et al., 1994; Vicente, 1999) using an abstraction hierarchy representation. The abstraction hierarchy shows how the physical forms (objects and material) and physical functions (low-level processes) are "exploited" by generalised functions (processes that the system needs) and abstract functions (system priorities and values) to help the scheme fulfil its functional purpose (do what it is meant to do) in the best possible way.

A challenge for information design for hydro operations is to provide a view of how the generalised functions (everyday working functions of the scheme) are run so as to minimise, maximise or preserve the values at the abstract function level—a key goal of "ecological interface design" (EID). Very often, interfaces are rich in detailed information about physical forms and processes, but they have little information about functions, priorities, and purposes—and such information tends not to be integrated. When considering representation design for hydro operations we need to define what the higher-order relations are.

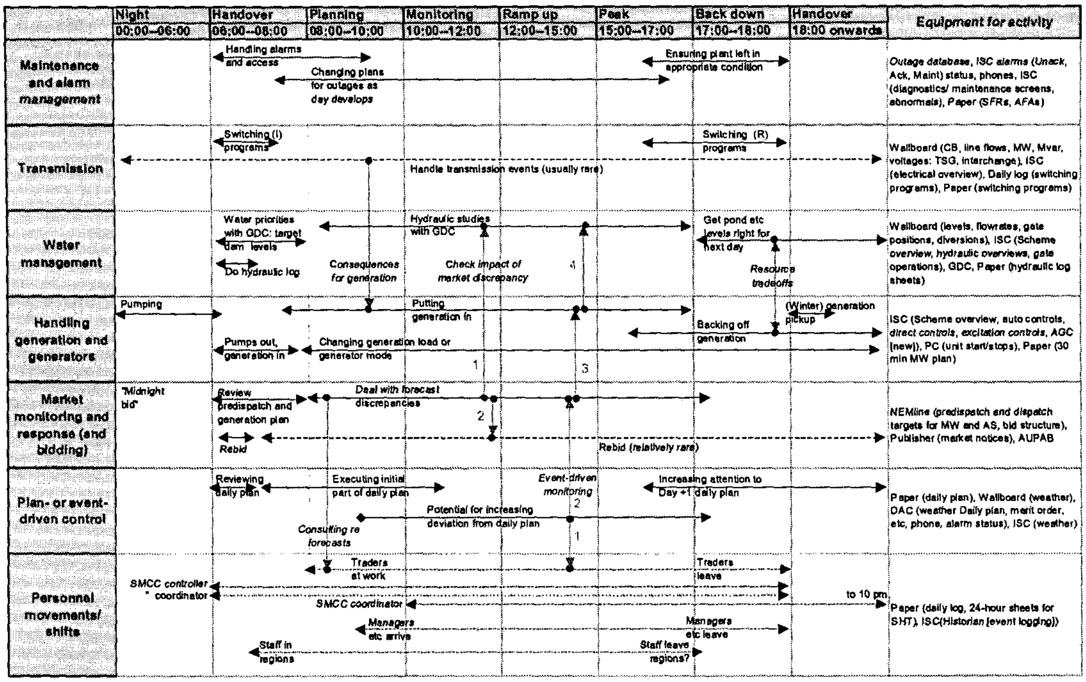

Figure 2: Activity analysis framework for hydro scheme control showing the prototypical contexts in which control tasks will occur

Challenges of work domain analysis for hydro operations in a deregulated market. Applying cognitive work analysis to new domains often requires interpretation of the fundamental principles of the approach so that those principles can be effectively adapted to the new domain (Miller & Sanderson, 2003). The challenges we have experienced modelling hydro scheme control in the context of a dynamic deregulated energy market involve finding a way to model (1) control of the energy source and the energy transformation process and (2) value associated with participation in the electricity market, through (3) the varying economic value of the energy source when in different physical locations and at different times.

As others have noted, the abstraction hierarchy formalism for work domain analysis (eg Figure 3) was not initially developed to represent financial systems although some first investigations have produced useful results (Achonu & Jamieson, 2003). Our challenge is a compound one: we need to find a way of conceptualising and representing the flow of energy and value across these different subdomains. Simply elaborating the nodes in the initial work domain analysis shown in Figure 3 is an inadequate approach—we are having to think at a fundamental level what the balances, processes and constraints are in this new domain that will create a solid foundation for representation design. At present this means that we are thinking in terms of the conversion rules between the different domains involved. In order to measure the effectiveness of displays based on these ideas, as we wish to do, we are also reconceptualizing the "object of control" at the abstract function level to be a higher-level derivative, such as the varying economic value of the energy source.

Applying EID interfaces in an installed base. As various authors have shown, advanced function display systems based on principles of EID appear to be feasible both when assessing performance with human operators who have extensive experience with a conventional interface (Jamieson, 2002) and when appending such displays systems to a conventional installed base (Yamaguchi & Tanabe, 2000). Our vision is that displays representing the higher-level concepts that our work domain analyses are leading to can be constructed on the installed information system base.

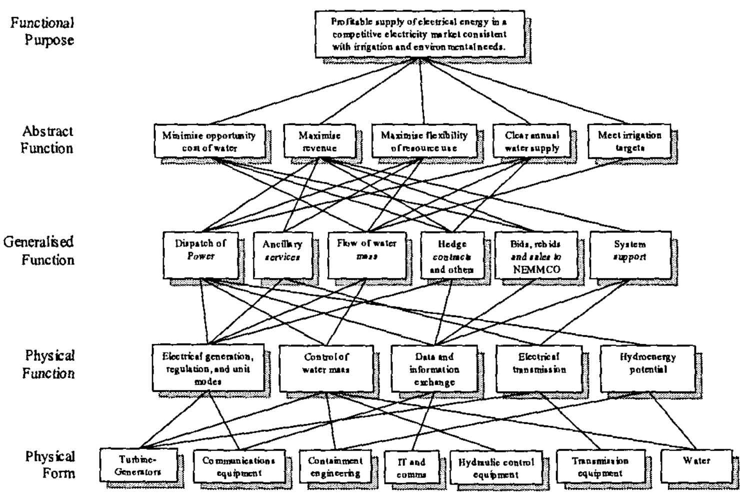

Figure 3: Simplified initial abstraction hierarchy representation of the hydro scheme control work domain.

PD, end-user authoring, and display design

EID provides a formal way into designing the user interface. However, in hydro scheme control rooms one often finds that end users are already working towards that goal. Human factors and HCI practitioners usually do not think of power generation as an area in which participatory design (PD) and end-user authoring of information systems might be effective. However, the evolution of information technology, combined with the less regulated hydro generation environment, mean that end-user authoring can have a central role in the design of the control room information environment. This can lead to some useful discoveries.

The introduction of windows-based Supervisory Control And Data Acquisition (SCADA) interfaces into the control room has brought greater flexibility for the client in how interfaces might be configured, and therefore the need for greater client involvement in specifying the interface configurations needed rather than relying upon the vendor's in house human engineering expertise. In an organisation in which there are a few highly committed and technically sophisticated individuals, as in a control centre, end-user involvement can be seen at all levels. For example, in the period leading up to the deregulation of the Australian electricity markets, when many generators were putting in place new technology in order to cope with market demands, personnel at the hydro scheme we observed used the interface design tools accompanying the SCADA system to develop key information displays in-house. During a later development of a new AGC system, hydro scheme control room personnel again played a critical role, taking it in turn to spend several weeks overseas with the vendor, working to ensure delivered functionality and presentation would fit operational needs. In addition, continuous improvement teams continually address deficiencies identified either through controller reports or more formal analysis.

Given this greater flexibility of the interface development, the client's involvement in interface development can now extend well beyond the delivery period of the SCADA system. However, end user participation can extend even further when control room information systems make graphical user interface authoring tools available to end-users during real time operations. Specifically, some such tools allow users to take real-time or near real-time values and to represent them either as a numerical readout or as a property or visual attribute of a graphical object on the screen. The result has been that early adopters amongst the controllers have developed "personal" user interfaces and used them in an exploratory fashion during their own shifts. Such personal user interfaces may integrate information that otherwise would have to be sought laboriously over multiple screens or they may represent higher-order Scheme properties in a more effective way.

A small amount of analysis of the most successful personal user interfaces indicates that such interfaces often represent information at a higher level of abstraction and a greater degree of aggregation (often achieved through integration) than many of the more formally developed displays. When controllers express—through their design efforts—their expert judgments about what constitutes the right information at the right time in the right format, their judgments reflect some of the principles of EID (Vicente & Rasmussen, 1990) supplemented with semantic mapping principles (Bennett, Nagy, & Flach, 1997; Reising & Sanderson, 2002) and proximity compatibility principles (Wickens & Carswell, 1995). One example, captured at an earlier point in the observed hydro generator's control room context just two years after deregulation, can be described as follows:

> This personal user interface integrates Generation, Hydro, and Market subdomains at a high level of aggregation on the one display screen. Raise and lower reserves are shown (1) as numbers in boxes with arrows symbolising the raise or lower status, (2) in a bar chart format and (3) in a trend display of actual energy values. Frequency is shown in large digits. Generating areas (represented by one or more power stations) are shown as rectangles with a smaller rectangle indicating the proportion of total MW capacity being used. Storages are shown as volumes with lines indicating a fast or slow rate or increase or decrease in level.

It is significant that one personal user interface is in prominent use today as a key monitoring screen on the electronic wallboard of the hydro scheme control room we observed. As for the earlier example boxed above, it also presents information at a higher level of abstraction and integration than is readily from the formal SCADA interface. It also integrates information about target and actual generation for three important generating areas, and close at hand provides information about storage levels likely to be affected by generation.

Although personal user interfaces reflect how well a controller has absorbed the first principles of operation of a system, the goal of EID is to represent knowledge in objective, normative representations, rather than subjective, descriptive representations based on experience with the system (Vicente, 2002). The challenge for the designer, then, is to develop formal models such as the cognitive work analysis models shown above, whether by inferring the first principles of system operation or by making inferences from the activities of experienced controllers.

Because hydro scheme controllers must coordinate effectively with corporate traders, an even greater challenge is to discover and represent important fundamental relations between hydro scheme operations and the priorities that are in effect when operating within the dynamic National Electricity Market. For example, it is possible that rather than model the human's task as achieving effective closed loop negative feedback to achieve goals, instead we might model the human controller as a participant in scheduling the release of a scarce resource with an opportunity cost (water) to a productive function (generation) against uncertainty.

Current and future activities

On the basis of detailed versions of the modelling described above, we are taking steps towards the development of advanced functional displays intended to increase the human controller's situational awareness, increase his ability to handle unanticipated events, and to increase quality of control performance against benchmark measures. We will contrast human controller performance with conventional hydro scheme control room displays vs advanced functional displays constructed according to the EID framework.

To this end we have developed a MatLab simulation of the combined generation, water management, market, and transmission characteristics of a large-scale hydro scheme operating within a simplified version of the NEM. Although simulations are common in the electricity industry, we believe our simulation of the generator's view of the physical and market environment is rare, if not unique. The modular design of the simulation will let us easily swap out different kinds of interfaces and let us take evaluated human controller performance. Given our conceptualisation of the work domain as one in which fundamental principles involve energy conversion plus the varying economic value of the energy source when in different physical locations and at different times, and given the very broad range of the hydro scheme controller's role, it is critical to capture and manipulate these properties in an experimental microworld.

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References

Achonu, J., & Jamieson, G. (2003). Work domain analysis of a financial system: An abstraction hierarchy for portfolio management. *Proceedings of the 22nd European Annual Conference on Human Decision Making and Control (EAM2003)*. Linkoping, Sweden, June 2-4. pp. 102-109.

Bennett, K. B., Nagy, A. L., & Flach, J. (1997). Visual displays. In G. Salvendy (Ed.), *Handbook of Human Factors and Ergonomics (2nd edition)*. New York: Wiley.

Crone, D., Sanderson, P., & Naikar, N. (2003). Using cognitive work analysis to develop a capability for the evaluation of future systems. Paper submitted for publication in *Proceedings of the 47th Annual Meeting of the Human Factors and Ergonomics Society*. Denver CO, 13-17 October.

Hoffman, R. R., Crandall, B., et al., (1998). Use of the Critical Decision Method to elicit expert knowledge: A case study in the methodology of Cognitive Task Analysis. *Human Factors*, 40(2), 254-276.

Hollnagel, E. (2002). Time and time again. *Theoretical issues in Ergonomics Science, 3*(2), 143-158.

Human Systems Engineering Group of the IEE (1999). *People in Control: An International Conference on Human Interfaces in Control Rooms, Cockpits, and Command Centres*. University of Bath, UK. 21-23 June.

Human Systems Engineering Group of the IEE (2001). *People in Control: The Second International Conference on Human Interfaces in Control Rooms, Cockpits, and Command Centres*. UMIST, Manchester, UK. 19-21 June.

Jamieson, G. (2002). Empirical evaluation of an industrial application of ecological interface design. *Proceedings of the 4th Annual Meeting of the Human Factors and Ergonomics Society Meeting*. Baltimore, MD.

Miller, A., & Sanderson, P. (2003). An Alternative ADS for the Analysis, Design and Evaluation of Information Representations in the ICU. *Proceedings of the 22nd European Annual Conference on Human Decision Making and Control (EAM2003)*. Linkoping, Sweden. pp. 95-101.

Moray, N. (1986). Monitoring behavior and supervisory control. In K. R. Boff, L. Kaufmann, Y J. P. Thomas, (Eds.), *Handbook of perception and human performance*. (Chapter 45). New York: Wiley.

Moray, N. (1997). Human factors in process control. In G. Salvendy (Ed.), *Handbook of human factors and ergonomics (2nd edition)*. NY: Wiley.

NEMMCO (1997). *Australia's National Electricity Market: An introduction*. Sydney, NSW: NEMMCO Ltd.

Noyes, J., & Bransby, M. (2001). *People in Control: Human factors in control room design*. Stevenage, UK: The Institution of Electrical Engineers.

Rasmussen, J., Pejtersen, A. M., & Goodstein, L. P. (1994). *Cognitive systems engineering*. New York: Wiley.

Reising, D. C., & Sanderson, P. (2002). Ecological Interface Design for Pasteurizer II: A Process Description of Semantic Mapping. *Human Factors*, 44(3).

Roth, E. & O'Hara, J. (2002). *Integrating digital and conventional human system interfaces: Lessons learned from a control room modernisation program*. Washington, DC: NRC (NUREG/CR-6749).

Sanderson, P. M. (2003). Cognitive Work Analysis. In J. Carroll (Ed.), *HCI Models, Theories, and Frameworks: Toward an Interdisciplinary Science*. New York: Morgan-Kaufmann. (To appear April)

Sanderson, P., & Naikar, N. (2000). Temporal coordination control task analysis for analysing human system integration. *Proceedings of the Joint Meeting of the Human Factors and Ergonomics Society and the International Ergonomics Association (IEA2000/HFES2000)*. Santa Monica, CA: HFES. Vol 1, Pp 206-209.

Schraagen, J., Chipman, S., & Shalin, V. (2000). *Cognitive task analysis*. Mahwah NJ: LEA.

Sheridan, T. B. (1997). Supervisory control. In G. Salvendy (Ed.), *Handbook of human factors and ergonomics (2nd edition)*. New York: Wiley.

Vicente, K. J. (1999). *Cognitive work analysis: Toward safe, productive, and healthy computer-based work*. Mahwah, NJ: Lawrence Erlbaum Associates.

Vicente, K. J. (2002). Ecological interface design: progress and challenges. *Human Factors*, 44, 62-78.

Vicente, K. J., & Rasmussen, J. (1990). The ecology of human-machine systems II: Mediating "direct perception" in complex work domains. *Ecological Psychology*, 2(3), 207-249.

Wickens, C. D., and Carswell, C. M. (1995). The proximity compatibility principle: its Psychological Foundation and Relevance to Display Design. *Human Factors*, 37, 473--495.

Wong, B.-L. W., (2000). The Integrated Decision Model in Emergency Dispatch Management and its Implications for Design. *Australian Journal of Information Systems*, 7 (2), 95-101.

Wong, B.-L. W., (2002). Data analysis for the Critical Decision Method. In D. Diaper and N. Stanton (Eds.), *Task analysis for human-computer interaction*. Mahwah, NJ: LEA.

Wong, W. & Blandford, A. (2002) Analysing Ambulance Dispatcher Decision Making: Trialing Emergent Themes Analysis. *Proceedings of the combined annual meeting of the Ergonomics Scoeity of Australia and the Computer Human Interaction Special Interest Group (HF2002)*. Melbourne, Australia, 24-28 November..

Yamaguchi, Y. & Tanabe, F. (2000). Creation of interface system for nuclear reactor operation: practical implication of implementing EID concept on large complex system. *Proceedings of the Joint Meeting of the Human Factors and Ergonomics Society and the International Ergonomics Association (IEA2000/HFES2000)*, Vol. 1, pp. 571574. Santa Monica, CA: HFES.