Sanderson, P., Memisevic, R., & Wong, B.-L. W. (2004). Analysing cognitive work of hydroelectricity generation in a dynamic deregulated market. Paper to be published in Proceedings of the 48th Annual Meeting of the Human Factors and Ergonomics Society, 20-24 September, New Orleans, LA.

ANALYSING COGNITIVE WORK OF HYDROELECTRICITY GENERATION IN A DYNAMIC DEREGULATED MARKET

Penelope Sanderson[1], Rizah Memisevic[1], and William Wong[2]
[1]ARC Key Centre for Human Factors and Applied Cognitive Psychology
The University of Queensland, St. Lucia, Queensland, Australia
[2]Interaction Design Centre, Middlesex University, London, UK

Much electrical generation in the developed world is now conducted within deregulated energy markets, providing new layers of uncertainty for human controllers and new challenges for analysts wishing to understand and support cognitive work. In this paper we outline some of the challenges encountered when attempting to describe the work domain of hydroelectric power generation in a dynamic deregulated electricity market. The market component of the work domain analysis appears not to be readily amendable to breakdown as a familiar functional structure. Control task analysis is complicated by the fact that the human operator is the frontline, real-time, manager of business risk. Different epochs of planning may require separate functional structures.

INTRODUCTION

Performing Cognitive Work Analysis (Rasmussen, Pejtersen, & Goodstein, 1994); (Vicente, 1999) for hydroelectricity generation in a deregulated market in a way that usefully informs control room design is very challenging (Sanderson, Memisevic, Wong, & Choudhury, 2003). Ensuring that analyses are framed so as not to misrepresent key characteristics of the work domain or of control tasks is a normal and expected part of cognitive work analysis. However, finding the right framing for a work domain that has qualitatively different properties from previous examples can present unexpected challenges. In this paper we outline some of these challenges, focusing on Work Domain Analysis and Control Task Analysis. We outline factors introduced when considering the impact of a dynamic deregulated electricity market on the domain of electricity generation, on the role of hydropower plant controllers, and on the analyst’s ability to perform work domain analysis and control task analysis.

HYDROPOWER DOMAIN PROPERTIES

In a deregulated electricity market, electrical power and related services (frequency and voltage control) are no longer provided through state government based regulation. Instead, each generating company is in the business of managing financial risk as it sells active power (MW) in response to immediate demand. Related services such as frequency control for regulation and contingency are now also bid into a spot market at a hoped-for price (a spot market is a cash market for immediate delivery) while the voltage control continues to be in the form of longer term contract arrangements. The financial motivation for deregulation is the anticipated lower long-term cost to society of producing electricity. For the individual generating company, however, the result of deregulation is much greater exposure to risk. The hydropower plant (HPP) controller and trader are the frontline managers of this risk.

Figure 1 shows some of the areas that are integrated in HPP control. The process of generation itself is shown with a shaded background and is the part of HPP control that is most similar to prior treatments of energy control (typically NPP control) in the CWA literature. In the HPP case, *mass transfer* refers to the movement of water through natural and manmade structures across a hydroelectric scheme. Natural inflow cannot be controlled. Storages may be very large or they may be very small and therefore vulnerable to emptying or spilling in a matter of hours or even in less than an hour if not appropriately managed. *Energy transfer* refers to the conversion of hydro potential energy to kinetic energy and finally to electrical energy. In the NPP domain, most attention has been paid to the control of mass and energy in the context of serving base electricity demand. There are usually no uncertainties about whether the energy source (fuel rods) will be available. In contrast, in the HPP domain, where water mass is the energy source, there may be considerable uncertainties depending on weather conditions, runoff levels, prior demand, location of the water, and so on.

Because of the relative simplicity of hydropower generation as opposed to nuclear, the work of a single controller ranges over a broader range of concerns than simply control of mass transfer and energy transfer. Functions that are the responsibility of a team in a NPP are usually the responsibility of just two (daytime) or one (nighttime) operators in the HPP context. However, the arrival of the deregulated market has required the individual human controller to understand the impact of market dynamics on HPP operations.

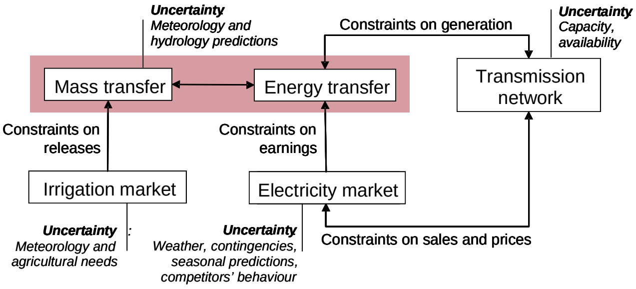


Figure 1: Hydropower generation—subdomains, sources of constraints, and uncertainties.

Most HPPs operate within an *irrigation market* as well as an energy market. Irrigation contracts will impose maximum and minimum water release constraints over fixed periods (years, months, or weeks)—constraints that must be met despite uncertainties in meteorological conditions and changing agricultural needs.

HPPs can be peak providers rather than base load providers. Rather than aiming to run at 100% power for months at a time, the HPP could seek to support peak demand and provide reserve power and contingency services (raising or lowering generation very quickly in response to need) to the electricity market. The *electricity market* is volatile and highly competitive. Uncertainties come from weather, contingencies in the system (sudden changes in electrical demand or load), seasonal variations, and the behavior of competitors. These factors will constrain how much is earned during the energy transfer (generation) process.

Finally, electricity cannot be stored but instead must be immediately transmitted. Transmission lines may have varying capacity, depending on network and weather conditions, and may or may not be available due to outages and maintenance. Such constraints in the *transmission network* will constrain how much electricity a HPP can generate, where it can sell its electricity, and what prices it will receive.

HYDROPOWER CONTROL PROPERTIES

It is difficult to understand the hydroelectric power plant operator's control tasks, and to design information systems to support them, without understanding the relation between system uncertainties and market strategy. Market strategy motivates control tasks and supplies principles for how the unexpected will be handled. Although business objectives do not originate with the human controller, in the peak power business the human controller is the agent of business objectives in a way that is less apparent in other forms of power generation.

What is the impact of the deregulated market on the human controller's tasks? Because a generating company is in the business of managing risk, it plans its operations as far into the future as it can but continually refines plans for each day as that day approaches (see Figure 2). When it comes to real-time control, human controller and traders are the frontline agents of corporate strategy.

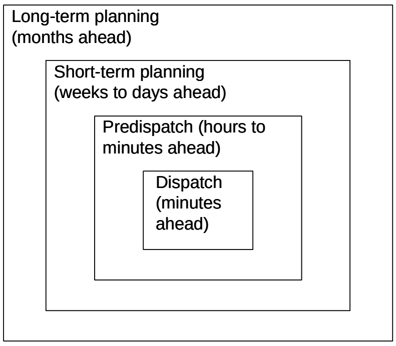


Figure 2: Relation of long-term planning to real-time dispatch for HPP control.

As shown in Figure 2, *long-term* strategic plans for water release and generation are made months ahead. They are based on historical data about water runoff, water storage levels, electricity demand, and market prices. As previously distant moments come closer, longer-term strategic plans are refined in light of better forecast information. *Short-term* plans look forward weeks or days, and represent tactics for implementing the long-term plan in terms of where water should be moved and how much generation should be done for what price on particular days.

Immediately prior to each dispatch day, a bid is made into the central market operator that reflects how much electricity (and other services) the company wishes to sell and for what price. The central market operator produces a *predispatch* schedule for generation that is displayed in the generating company's control room and is updated through the market day as needs change. In this manner, plans move through different but interconnected parts of the organization over time, and through different but interconnected people, until they are bid into the market.

Guided by the predispatch schedule, the human controller then prepares the plant for the real-time execution of the predispatch plan, working around disruptions and outages that inevitably occur. Just minutes ahead, the company is told exactly how much electricity (and other services) it will be providing, or *dispatching*, to the market. The human operator supervises the operation of automated control processes that execute the dispatch.

The human operator tries to preserve the objectives in the daily operational plan, and usually also in the predispatch schedule, but sometimes the assumptions on which the plan is based are challenged or the plan becomes infeasible. Then the human operator interprets and adapts corporate strategy in real time (see Figure 3). If conditions change, companies can change their bids to see if the central market computer will reallocate demand in a way that suits them better. Because spot prices can be very volatile, companies also make direct contracts involving financial instruments such as swaps or caps with their customers to remove their risk exposure to spot market fluctuations. Additionally, a HPP can have imposed irrigation requirements and/or could enter into water release contracts with their customers.

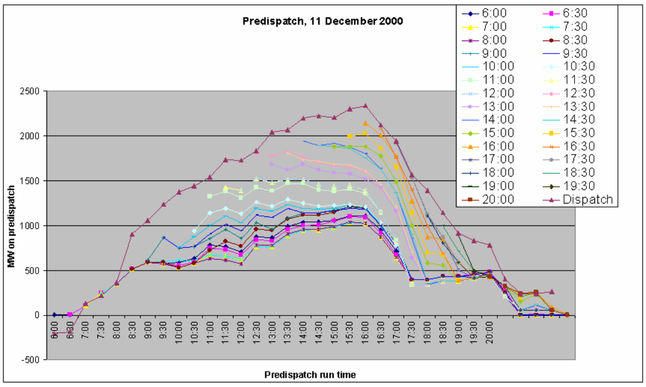
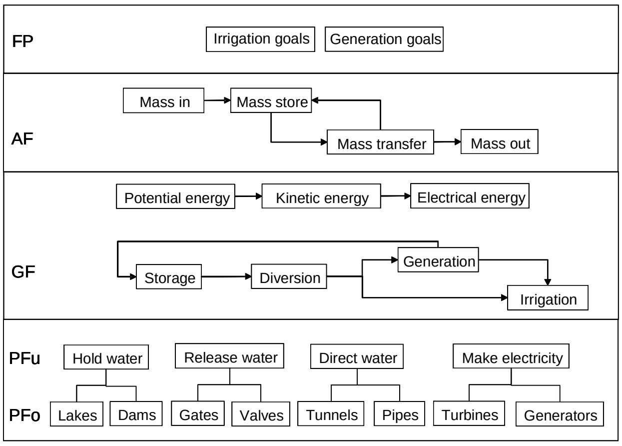


Figure 3: Predispatch schedule for a hydroelectric generating company updated at 30-minute intervals for an unexpectedly hot day.

The HPP controller’s job can become extremely busy in the face of uncertain information and electricity market dynamism. Figure 3 presents historical data from an Australian National Electricity Market archive, showing how the amount of active power a hydroelectric company expected to generate during a very hot summer day changed every 30 minutes as projections for power demand were updated. Peak prices reflected the increasing demand and the company made multiple rebids into the market to meet the demand (see multiple lines starting at successive 30-minute intervals). By early afternoon, it was clear that continuing to meet the peak demand required switching to use water that was otherwise being held in reserve. Therefore, during the dispatch day, the human operator together with the company’s trader revised the current trading plan in light of the company’s ultimate purpose of minimizing risk, in order to meet an unanticipated but profitable demand. The uppermost continuous line in Figure 3 indicates the final amount of active power dispatched by the hydroelectric company that day—more than twice the initial projections.

HYDROPOWER WORK DOMAIN ARCHITECTURES

Work Domain Analysis (WDA) can readily identify the functional structure of a HPP as an engineering domain, highlighting properties, functions, and priorities of generation and water management that should be made visible to the human operator. A very simplistic example is given in Figure 4(a). However, such a representation fails to capture properties, constraints and uncertainties associated with the irrigation market, the electricity market, and the transmission network.



Regulated industry	**Deregulated market**
Purposes	***Purposes***
Irrigation, power, and electricity system security (System Security was ensured by State Government Departmental Agreements and the System Operator could allocate tasks without concern for costs involved.)	Irrigation, power, and corporate profit (Code Compliance industry wide to ensure Quality of Supply. System Security is centralized responsibility with the National Electricity Market Operator but some Security Services called Ancillary Services are marketed products. Central Operator now needs to procure these through market mechanisms)
Priorities and functions	***Priorities and functions***
Invariant relationships are safe *operating limits* of the system	Invariant relationships are *risk relations and constraints* between HPP operation and market factors.
Processes and objects	***Processes and objects***
Generation units, switches, transmission lines, water levels, channel flows, etc.	Financial risks, predicted market demand, spot prices for electricity, ancillary services, etc.

Figure 4: (a) Abbreviated WDA of HPP engineering functional structure. (b) Abbreviated framework for WDA of HPP intentional functional structure.

Prior to deregulation, electricity was sold by state government based agreements into a highly regulated, relatively stable arrangement. Providing frequency or voltage support for the grid was a service provided when required. After deregulation of the electricity industry, however, and the introduction of a spot market in electrical energy and support services for the grid, this relatively stable situation has disappeared.

Under deregulation, generation follows a corporate strategy for profitability. In Australia, all of the generation participates in the moment-by-moment movement of the spot market. Since there are financial contracts to cover the spot market volatility risk as explained earlier, the contracts in turn could influence participant bids and thus impact on the spot market. In addition there could be irrigation requirements and water release contracts, which could influence a participant's behaviour. A key problem for WDA is showing the interconnection between generation, water management, and market activity.

One strategy is to identify the different domains the operator's activities span and to treat them as interconnected subdomains (bottom of Figure 4b). However, this representation does not indicate the nature of the connections between the subdomains. Moreover, it does not reflect the overweaning importance of survival in the market. Accordingly, we might subsume hydro control and generation control under market participation (top right of Figure 4b). Unfortunately, building a WDA from this basis fails to represent accurately the means-ends relation between the three subdomains. Alternatively, we might view the three subdomains as part of a larger abstraction-decomposition space (top left of Figure 4b). While probably closer to a useful representation, it still leaves the nature of market properties and its connections to be identified. A qualitatively different approach is needed.

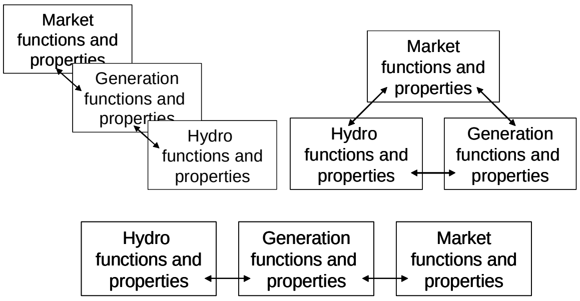


Figure 6: Alternative architectures for representing hydroelectric power generation market participation

A simplified version of a unified WDA for the HPP work domain that combines market, hydro and generation functions and properties was provided in Sanderson et al (2003). Even so, it has proven considerably more difficult than expected to turn such a high-level description of purposes, priorities, functions, processes and objects into a more detailed description with an unambiguous syntax adequate for synthesizing display design (Lind, 2003). The domain being captured is probably larger and more various than seen in most other real-world applications of EID (eg Jamieson, 2002). Some sources of the challenge of the market are discussed below.

CHALLENGE OF THE MARKET

The nature of the deregulated energy market requires a different perspective from the one used when analyzing cause-effect relationships. Although generation and transmission are causal in nature, they are driven by highly dynamic and intentional market forces. For cognitive work analysis, the market, the generation, the hydraulic and transmission systems are tightly coupled and needs to be viewed as one system, even though the production and transmission system may be nested within the market environment.

The older regulated market was fairly stable. The goal of the electricity generating companies was to ensure that target production outputs were met. Reacting to or compensating for fluctuating market demand was a responsibility but it was not a market contestable commodity.

However, in the deregulated market, electricity utility operators which to run their plants in a way that maximizes opportunities in the market. Market opportunities are based on competitive pricing, which varies as spot prices change, as demand changes, or as resources likely to be employed enter into different price bands of the market. Market behavior and properties of the market are not predictable from laws of nature, but are instead based on intentions of market traders, demand for electricity, and the competitive responses of other electricity producers in the market.

The purpose of the operator in driving the system as close as possible to the market constraints is to minimize financial losses. Breaching the limits can lead to performance penalties, and producing electricity too far away from constraints reduces the potential profit. These constraints are no longer invariant relationships of the engineering infrastructure (generation, water, transmission), but are new invariant relationships that did not exist before the market was deregulated, and are based on the intentional properties of the deregulated market. These intentional properties are reflected in market factors such as spot prices in the different markets, bids, raise and lower reserves and other ancillary services, rather than as limits of the physical performance of the production infrastructure. Thus production optimization must occur in terms of market intentions rather than just in terms of the physical limits such as system safety and capacity.

Regardless of the success or lack of success reported in previous research, the principle of identifying and making the invariant relationships and constraints visible is crucial. What we are learning from this research is that (i) controlling the production of electricity in the new deregulated electricity market is markedly different from the previously more stable environment; (ii) that the physical (causal) production system is “nested” within a highly intentional, competitive market-driven environment, and (iii) the physical invariants and constraints of the production system must be made visible within the context of the market’s intentionally-based invariant relationships and constraints. When all these relationships are visible, it may be easier for the production controller to operate the system “close to the constraints”, thereby maximizing profits. These constraints are themselves dynamic and multi-dimensional and they interact between the physical world and the market world, rather than just being fixed performance or safety criteria such as temperature or tank pressure.

The properties described above capture some of the character of market operations in a deregulated electricity market. Market properties are not physical but instead are financial, intentional (Rasmussen et al., 1994) and non-deterministic. The “transfer function” of the market continually changes as a function of participants’ beliefs, competitors’ behavior, risk appetites, network constraints, uncertainties in forecasts, and so on. The most successful modeling of the market is not analytic or causal, but instead is based on artificial intelligence methods, where trend and noise can be separately modeled (Zhang & Dong, 2001). The determinants of trend and noise are themselves continually changing.

In sum, the first principles of operation of the spot energy market appear to resist means-ends modeling as a functional structure. Although it appears that effective information representations will be those that provide market intelligence, longer-term historical trends, and predictions from AI modeling based on postulated timeframes of activity, the details of this may have to emerge from separate formalisms.

CONCLUSION

In summary, performing WDA and CTA as part of describing the cognitive work of hydroelectric power plant operators in a deregulated environment quickly takes the CWA analyst out of traditional engineering areas associated with power generation into intentional areas such as spot market dynamics and the management of financial risk. Although there is promising work on individual aspects of power generation (Overbye, Sun, Wiegmann, & Rich, 2002; Vicente, Moray, Lee, Rasmussen, Jones, Brock & Djemil, 1996) there are few prior examples of CWA products for domains like a highly dynamic, deregulated spot electricity market. Moreover, there appear to be no CWA analyses or display concepts for dynamic market structures. Closer inspection reveals some of the challenges to creating them. Operators could possibly be aided by a good representation of the “functional structure” of the market, but the deregulated spot market for energy and associated services is proving difficult to analyze in those terms.

ACKNOWLEDGMENTS

We acknowledge the contributions of Sanjib Choudhury to the research behind this paper. This research was supported by Australian Research Council grant C00107069 to Sanderson and Wong.

REFERENCES

Jamieson, G. A., (2002). Empirical Evaluation of an Industrial Application of Ecological Interface Design. *Proceedings of the 46th Annual Meeting of the Human Factors and Ergonomics Society*, Santa Monica, CA: HFES. (pp. 536-540)

Lind, M. (2003). Making sense of the abstraction hierarchy in the power plant domain. *Cognition, Technology and Work*, 5, 67-81.

Memisevic, R., Choudhury, S., Sanderson, P., & Wong, W. (2004). Integrated power scheme simulator for human-system integration studies. Paper provisionally accepted for publication in *Proceedings of the Australian Universities Power Engineering Conference (AUPEC04)*. September. St Lucia, Qld.

Overbye, T., Sun, Y., Wiegmann, D., & Rich, A. (2002). Human factors aspects of power system visualizations: An empirical investigation. *Electric Power Systems and Components*, 30, 877-888.

Rasmussen, J., Pejtersen, A. M., & Goodstein, L. P. (1994). *Cognitive Systems Engineering*. New York: John Wiley & Sons, Inc.

Sanderson, P., Wong, W. B.-L., Choudhury, S., & Memisevic, R. (2003). Hydro scheme control in a deregulated environment: Cognitive work models and design implications. *Proceedings of the 47 th Annual Meeting of the Human Factors and Ergonomics Society*. (pp. 458-462). HFES: Santa Monica, CA.

Vicente, K. (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., Moray, N., Lee, J., Rasmussen, J., Jones, B., Brock, R., & Djemil, T. (1996). Evaluation of a rankine ccle display for nuclear power plant monitoring and diagnosis. *Human Factors*, 32, 506-521.

Zhang, B. L., & Dong, Z. Y. (2001). An adaptive neural-wavelet model for short-term load forecasting. *International Journal of Electric Power Systems Research, 59*, 121-129