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Shapes of human control in time: Models and a hydropower system example

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Abstract

In cognitive ergonomics, we need to find ways of modelling the temporal fit of people to the systems in which they work. This paper reviews ways that time has been handled in models of human-system integration over the last 60 years. Then the temporal properties of hydropower system control are discussed from objective and controller-centred points of view. These analyses lead to the specification of displays that support reasoning in two timeframes.

Introduction

Within cognitive ergonomics, time has been handled in different ways when analysts consider the role of the human controller. Four frameworks for handling time are introduced here: manual control, supervisory control, discrete process control and the European work psychology tradition. Ideas from these frameworks are applied to the problem of supporting the role of hydropower system controllers, and to the design and evaluation of displays geared to supporting two timeframes of problem solving in hydropower system control.

Modeling time in human-system integration

A useful starting point for understand the role time plays in human-system integration is Sheridan’s (1987) description of the different levels of coupling between human and task (see Figure 1) that occur in different kinds of systems. In some systems, such as traditional vehicles, the human is a direct or almost-direct manual controller, whereas in other systems, such as industrial processes or highly automatic or unmanned vehicles, the human is a supervisor of automated or intelligent systems.

Manual control. The manual control tradition of human factors uses control theory, which is a highly quantitative way of understanding and modeling the coupling of human and systems in time (McRuer & Jex, 1967; Sheridan & Ferrell, 1974; Rouse & Gopher, 1977). The systems most commonly and successfully modelled are vehicles—automobiles, ships, aircraft, and spacecraft. Block diagrams such as that in Figure 2 show the arrangement of properties of the human and the system. Figure 2 is a block diagram of driving while buffeted by wind. There is a desired path (see left of figure) that the driver attempts to travel by making inputs to the car that correct heading and position error created by disturbance and fed back perceptually to the driver. The manual control tradition continues to be a source of conceptual insight as well as practical insight into contemporary manual control problems such as telesurgery (Jagacinski & Flach, 2003). It provides us with temporal concepts such as lead, lag, delay, and with control performance measures such as stability.

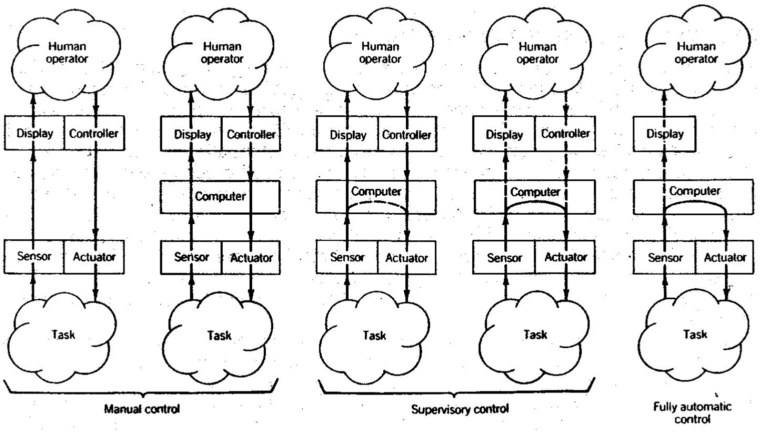


Figure 1. Relation between human operator and task across manual control, supervisory control, and automatic control arrangements (from Sheridan, 1987).

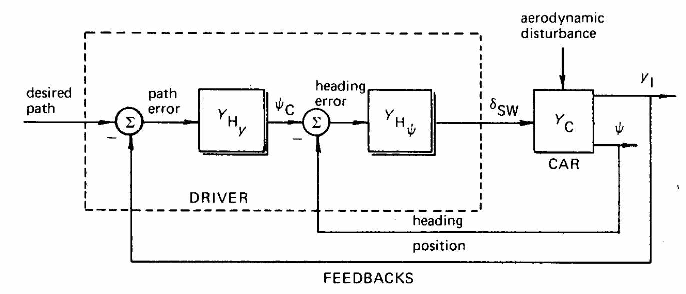


Figure 2. Block diagram of automobile driving while buffeted by wind (Weir, Heffley & Ringland, 1972).

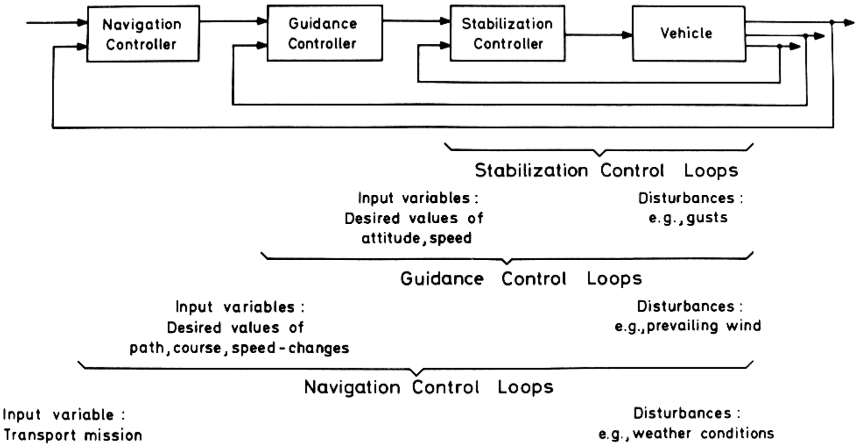


Figure 3. Block diagram of vehicle control showing hierarchical multilevel control loops (Johannssen, 1976).

Supervisory control. Challenges to the kind of control theory used in vehicle control came from inherently very slow processes in which humans make only intermittent intervention (Edwards and Lees, 1974). Challenges also came from systems in which the human supervises highly automated controllers of remote or hazardous processes, such as nuclear energy, electricity transmission, chemical processes or refining (Sheridan & Johannsen, 1976). Both require a different and more qualitative kind of modelling (Moray, 1986; Sheridan, 1987). Rather than involving direct manual control, the human's role relates to the more intermittent and cognitive tasks of planning, instructing, monitoring, intervening, learning (Sheridan, 1987).

Evident in the supervisory control parts of the Sheridan (1987) model in Figure 1 is the fact that the computer closes the control loop, separating the human from process dynamics. Figure 3 shows that with increasingly sophisticated control systems, a hierarchy of control loops is possible. The challenge for human operators in such systems is how to remain cognitively coupled with system dynamics and system state while “out of the loop(s)” (Bainbridge, 1983). From such challenges the idea emerged that human and system should work together as a *joint cognitive system* (Hollnagel & Woods, 1983; 2005) rather than as separate entities with disparate roles.

Discrete process control. The above traditions of research focus on continuous processes. There is a further tradition of research on the role of the human operator in discrete process control, such as manufacturing (Sanderson, 1989; MacCarthy & Wilson, 2001). Time is central to scheduling but it is handled as a discrete rather than continuous entity; activity at any point within a window of opportunity is as good as at any other point. The language of scheduling includes concepts such as the *due date* or deadline for a job to be completed, the *slack time* remaining before the job’s due date, and the eventual *lateness* of a job (including what we would think of as its earliness) with respect to its due date Scheduling rules impose priorities for dispatching (sending) jobs to processes—some of the simpler rules include choosing the job with the earliest due date (EDD) or least work remaining (LWR). Distinct nested cycles of planning, scheduling, and dispatching refine work requirements as dispatch time nears and uncertainties are removed (McKay & Wiers, 2003).

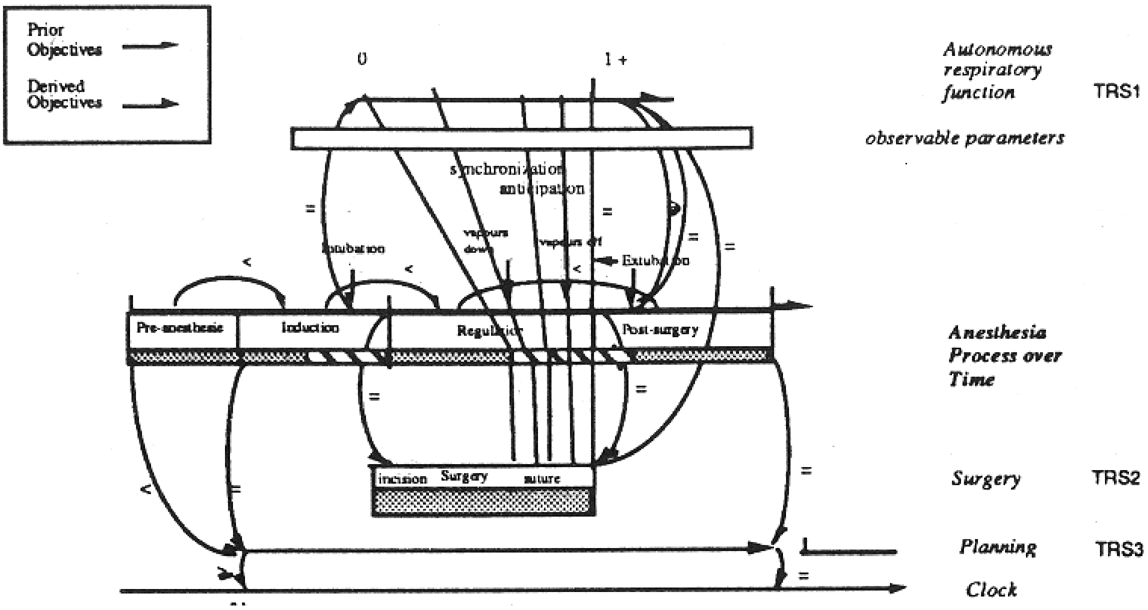


Figure 4. Juxtaposition of three temporal reasoning systems (TRS) impinging on the anesthesia process (Nyssen & Javaux, 1996). Symbols such as “<”, “=” refer to ordering constraints in temporal logic.

European work psychology. Alongside the above, and partly interwoven with it, has been the European work psychology tradition, with its strong emphasis on field investigation of workers’ actual activities (de Montmollin, 1991; De Keyser, 1991) rather than analyses of their tasks. Researchers in this tradition have characterised expertise as the acquisition of knowledge about temporal relationships (De Keyser & Piette, 1970) and have noted the contribution of mistiming to error (De Keyser, 1995). This tradition has promoted a more subjective or ecological concept of time, with an acknowledgement of cyclic rather than linear representations of time and with the concept of multiple temporal reference systems (TRS). The problem of temporal coordination between multiple humans and their systems is central to this work.

As an example, Figure 4 shows the relation of the anesthesia process over time to the hospital clock regulating scheduling (TRS3), to the timing of surgery (TRS2), and to the patient's respiratory function that the anesthetist must manage (TRS1) (Nyssen & Javaux, 1996). Concerns are the natural pacing and segmentation of time by critical activities and achieving coordination with others around such critical activities.

Partially related to the above tradition is the work of Hollnagel on what it means for a human operator to be in control of a process (Hollnagel, 1993; Hollnagel, 2002). The Nyssen and Javaux (1996) analysis is descriptive and does not provide a means for judging whether temporal demands have become too high. In his contextual control model (COCOM) Hollnagel puts time at the core, emphasizing that human control takes time, takes place in time, and responds to temporal constraints. Given a set of temporal constraints, controllers will consider several goals or only one goal; they will select action based on predictions, experience, hunch, or merely chance; and their evaluation of outcomes will be elaborate, detailed, concrete or merely rudimentary.

Figure 5 illustrates and parameterises the COCOM model (Hollnagel, 2002). The human contribution includes time to evaluate (T_e), time to select action (T_s), and the time window (T_w) to perform an action (T_p). The system contributions are time at which action becomes necessary (T_o) and the last finishing time for any action (T_{lft}), so that the time available to act (T_a) is T_{lft}-T_o. Given the relationship of T_a to T_e, T_s and T_p, control quality can be characterised that ranges from strategic to tactical to opportunistic to scrambled. Technological improvements or human adaptation increase the ratio of T_a to T_e, T_s and T_p.

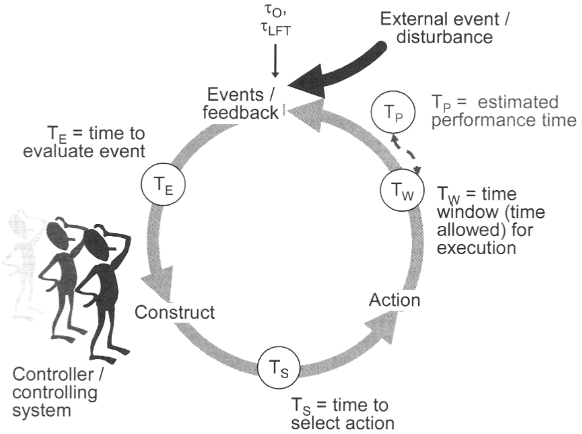


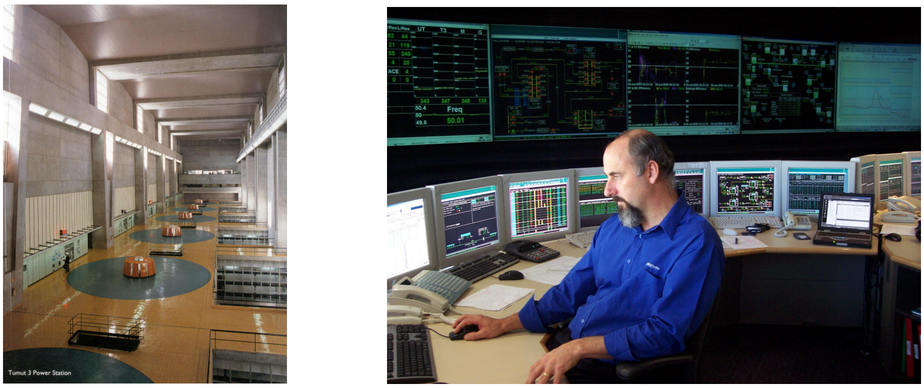
Figure 5. Hollnagel's contextual control model (COCOM) showing relationship between the controller's time and system time (Hollnagel, 2002).

Hydropower system control

Informed by the traditions reviewed above, we examined the role of hydropower system controllers working in Australia's deregulated electricity market and the temporal challenges such controllers face. The overall goal was to consider whether controllers are adequately supported by their information systems and whether improvements could be made (Memisevic, Sanderson, Choudhury, & Wong, 2005).

HPS controllers usually supervise the readiness of physical plant to respond to market signals. They start and stop generators to meet changes in demand (see Figure 6).

Hydropower system (HPS) control is a supervisory control process, but it has aspects similar to discrete process control—in particular its cycles of planning, scheduling and dispatching and its inherently “just in time” nature given that electricity cannot be stored. In what follows we provide a generic description of temporal aspects of HPS control in a deregulated market before considering HPS TRSs.



(Snowy Hydro Limited)

Figure 6. Hydropower plant controller supervises vast, remote physical plant.

Temporal properties of HPS control. Demand for electricity changes continually and a HPS is usually providing peak demand. Figure 7 shows how overall demand changes on an annual, weekly, and daily basis. There are peaks in demand in summer and winter (left graph) that are reflected in different profiles of demand during summer days and winter days (right graph). There is also a weekly cycle (centre graph), with demand greater during the week than at the weekend.

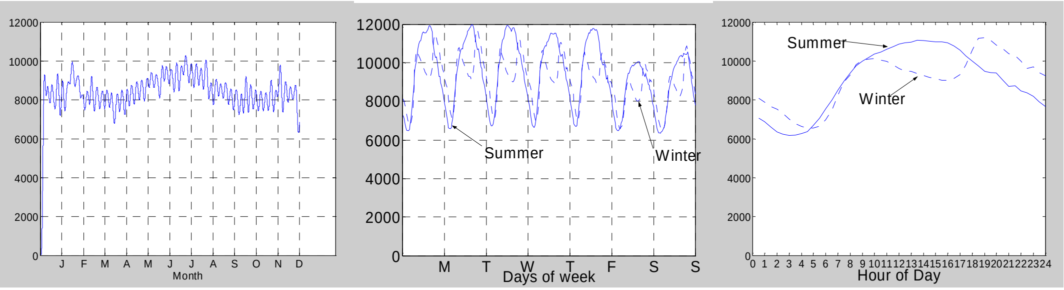


Figure 7. Profiles of demand (MW) for electricity in NSW across months of year, days of week (winter vs summer), and hours of day (winter vs summer) in 2004.

The graphs show average electricity demand from historical records and therefore do not show the range of natural variations and disturbances that inevitably happen. Profiles of the actual generation for a HPS company may vary due to an unusually hot summer, an unusually wet winter, and so on. Weekly profiles may change due to a public holiday. Daily profiles may change because of unpredicted weather variations, equipment failures in the electricity network, or a major political, cultural, or sporting event. In addition, a hydropower company’s response to electricity demand depends upon (1) the availability and expected value of the energy source (water), (2) prices negotiated for contracts and anticipated in the electricity market, (3) requirements to provide water for irrigation (HPSs typically have irrigation obligations as a condition of operation and/or as a source of revenue), and finally (4) whether the company’s bid into the market is successful so that it generates the amount it wants, when it wants.

As a result of the above uncertainties, the plan for how much generation should be done for a given week, day, and each 30 min interval of the day is successively refined as that week, day, and interval comes closer and uncertainties about weather, demand, network status and so on are removed (see Figure 8). There are therefore multiple cycles of planning, scheduling and dispatch for the generation that should be done, with plans progressing to different parts of the organisation as the moment of dispatch comes closer. Longer term planning will involve meteorology, hydrology, and economics. Closer to dispatch, plans will move forward to scheduling, where a more refined plan for several days will be determined. Prior to each generating day, that day's plan is finalised and a bid made to the market management company that details how much electricity the company wants to make from which parts of the system, and for how much money. The bid is either fully or partially accepted by the market management company as a predispatch schedule for the next day.

On the generating day the human controller on shift in the control room manages the execution of the final dispatch schedule according to the daily plan and responds to any contingencies—most notably those that make it necessary to make a new bid to the market management company to change the dispatch schedule. Working with the company's traders, the human controller provides a last line of "resilience" in the face of unanticipated last-minute variations in demand, resources, or market opportunities (Hollnagel, Woods, & Leveson, in press). For example, real-time business decisions sometimes must be made between using water to make short-term gains on the market vs preserving water for later use when even higher gains may be possible.

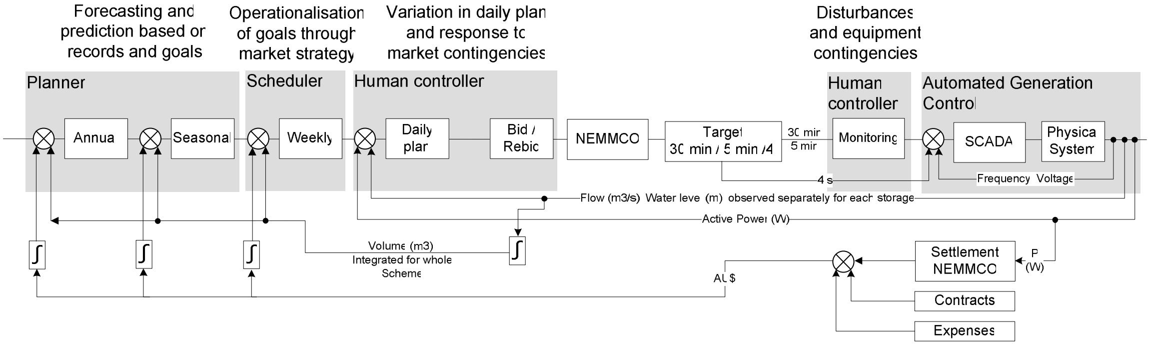


Figure 8. Cycles of generation planning, scheduling and dispatch, showing timeframes and controlling agency (courtesy of Rizah Memisevic).

Automated control and temporal constraints. The HPS controller is a supervisory controller, supported by sophisticated automated systems (Figure 1). Electricity travels at the speed of light—much faster than a human can exercise control in real time—and it cannot be stored. The human controller can decide on the mode of automatic control to be used, but for the most part he or she monitors the automated generation control system (AGC) and ensures that plant is ready to be called into service when scheduled, which may change at 5 min intervals, or when called upon in case of a contingency. Signals are sent from the market management company (NEMMCO) to the hydropower company's generators every 4 sec, well beyond the human controller's ability to react to even though outcomes can be monitored.

Water moves much more slowly than electricity, but still must be at the right storage in the right quantities at the right time, given annual, weekly and daily cycles of demand for electricity and irrigation. Irrigation targets normally need to be met on an annual, seasonal or weekly basis, freeing controllers from daily concerns on whether irrigation targets are met. However there are daily targets for water levels of all storages that controllers try to achieve, constraining real-time decision making about where a change in the generation profile should take place. Moreover, to protect equipment as well as the environment, water diversions can only take place at controlled rates.

Figure 9 provides a different view of the temporal constraints of hydropower generation (Memisevic, Choudhury, Sanderson, & Wong, 2004). Along the bottom are time periods or frequency bands at which cyclic events occur. At left are extremely rapid power system phenomena and control systems that are handled with automatic systems. At centre is the range of time periods or frequency bands at which the human controller perceives and acts. Vertical lines showing 4”, 5’ and 30’ represent the different cycle times of the market management company’s coupling with the HPS and its generators. Annotations note the timeframes or frequency bands of events in the water network or in short term storages. Over shorter timeframes the human coordinates generators and storages with dispatch targets but with a view to the goals for storage levels for the end of the day. At right are time periods or frequency bands of activity that involves longer term planning and that is usually outside the scope of attention of the human controller.

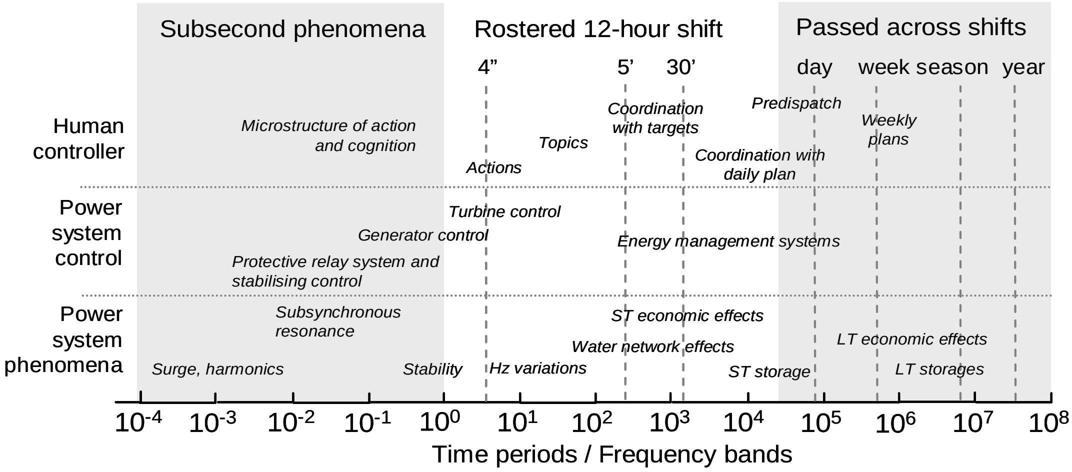


Figure 9. Timeframes of power system control (adapted from Memisevic et al., 2004).

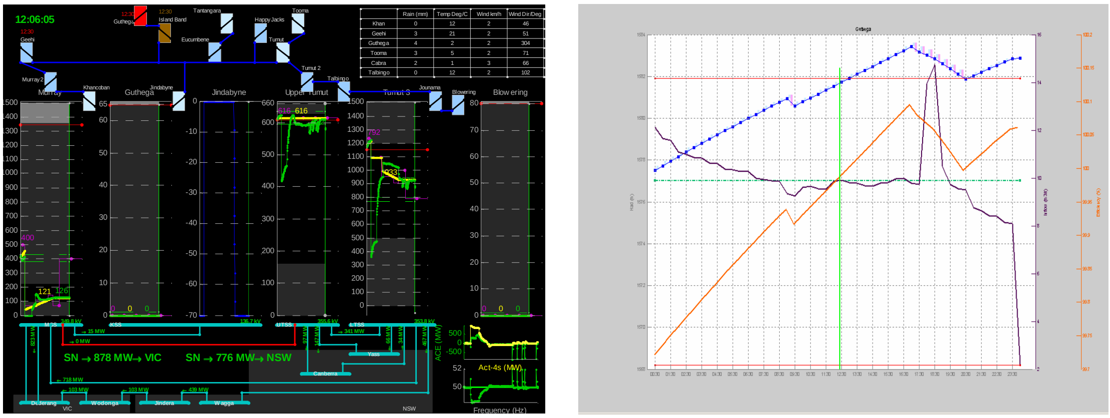
Temporal reference systems at work during contingencies. The above representations of the temporal properties of HPSs only start to convey the temporal constraints that the HPS controller faces when handling a contingency in real time. The timeframes in Figure 9 are not neatly nested but often must be considered simultaneously. In the following I use the concepts and terminology of both Nyssen and Javaux (1996) and Hollnagel (2002) to describe some of the complexities.

The first temporal reference system (TRS) is the market. If a contingency requires rebidding to the market, then the rebid will be captured during a one five-minute trading interval, where it will either be processed by the optimisation routine during that interval or in the next interval, with results being fed back to the HPS company in the subsequent trading interval. Using COCOM terminology (Hollnagel, 2002) the time available to act, T_a or T_{lft}-T_o, is divided into 5’ intervals where activity is equally valuable within the interval, but costs of delay may step up dramatically in the next 5’ interval. Rebids themselves take 1’ or so to construct and send, T_p, and the market optimisation takes time to complete, T_w, which must be considered.

A second TRS comes from generators themselves. If a market rebid is successful and there is a new generating target that requires starting up a new generator, it takes several minutes from starting the generator until it is generating at the required level to meet the new target. After the initial command from the HPS controller the start-up sequence is handled via relays and other automatic systems, but there is an inherent delay, part of which relates to the build up of speed in the turbine as valves are opened to let water through. Again, the delay adds to T_w.

A third and far more complex family of TRSs comes from water storages. For example, generators will run only as long as there is water available. Some storages above power stations are quite small and if the downstream power station is generating continuously and the upstream storage is not being refilled from elsewhere, the storage may reach its minimum level in hours or fractions of hours. The anticipated time at which the storage will run dry is a deadline, or T_{lft} , for ceasing further drainage of the storage. Similar T_{lft} deadlines exist for storages filling up below a generating power station and for controlled diversions and releases. A key problem for the HPS controller in planning the precise location of daily generation, or in handling contingencies, is knowing when such T_{lft} deadlines will occur and when corrective action, T_s, must start if generation is to continue. The HPS controller must integrate over time the water released relative to the capacity of the storage and should also consider the timing of effects on the broader water network.

When handling a real-time contingency, the HPS controller must engage in reasoning within and among these three TRSs, at least. Many other TRSs exist within HPS control, and many further interactions between TRSs exist. The above indicates how the idea can be operationalised in a complex system with many interacting elements, and suggests the cognitive complexity it imposes on the controller.



	Rain (mm)	Temp Deg/C	Wind km/h	Wind Dir/Deg
Khan	0	12	2	46
Geehi	3	21	2	51
Guthega	4	2	2	304
Tooma	3	5	2	71
Cabra	2	1	3	66
Talbingo	0	12	2	102

Figure 10 Displays for short-term coordination with energy targets (left) and for longer-term problem-solving about water storages (right) (Memisevic et al., 2005).

Display design and evaluation

Figure 10 shows two prototype displays we have developed in response to the above concerns plus further analyses (Memisevic et al., 2005; Sanderson, Li, Memisevic, Wong, & Choudhury, 2005). The leftmost graph supports short term coordination with energy targets and thereby the first two TRSs outlined above. The rightmost graph supports longer-term problem-solving about water storage levels and thereby the third TRS outlined above. A further graph, not shown here, supports an understanding of the potential economic impact of HPS configuration. Here a summary description is provided for the first two graphs, focusing on their most important properties in light of the temporal themes just discussed.

The leftmost graph integrates information about (moving counterclockwise from top right) weather, water storage status, generator readiness, transmission network status and power quality in order to support human controller activity in the 5’ to 30’ timeframe. The display also shows important constraints on changes that might be made in the short term, such as whether the generators are configured so that the company can respond instantly to any need for an increase or decrease in power, whether further capacity of this kind is available with the generators currently running, and whether transmission limitations constrain any of these possibilities. The water storage information on the leftmost graph covers factors relevant for the short term, such when the storage will arrive at a minimum or maximum storage level given the current dispatch schedule.

The rightmost graph represents longer-term information about a single water storage across the day. Maximum and minimum storage constraints are horizontal red lines at top and bottom and the target storage level for the end of the day is a horizontal green line. The blue line shows anticipated level if the current dispatch schedule is maintained—clearly goes above the maximum storage level so will need to be altered. Other lines show inflow and efficiency of use of water. Similar displays are available for all storages, both singly (as in Figure 10) and collected into an overview.

An initial evaluation of these displays has been completed as part of the PhD thesis of Xilin Li. Working in a HPS simulator, controllers handled contingencies with their normal displays or with their normal displays supplemented by the prototype displays in Figure 10. Controllers reported higher levels of situational awareness at levels SA2 (recognising system state) and SA3 (predicting future state) with the prototype displays. Moreover, out of a set of 10 overview displays including the current and prototype displays, controllers selected the two displays in Figure 10 as ones they would want to include on their wallboard (see Figure 6). Although there are several issues still to resolve, further analyses to perform and further investigations needed, results to date are promising.

Conclusions

Decades of investigation into the role of the human controller have given us a rich legacy of concepts to use when understanding the temporal properties of HPS control and the temporal constraints on how HPS controllers construct effective patterns of activity in response to contingencies. By examining the timeframes within which reasoning takes place and the timeframes that are the subject of reasoning, we can suggest control room enhancements that may lead to better response to contingencies.

Acknowledgements

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