PsychNology Journal, 2008
Volume 6, Number 3, 321 – 345

Applying a Cognitive Engineering Approach to Interface Design of Energy Management Systems

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ABSTRACT

This article presents a case study of the user interface design of a grid (energy) management system. The theoretical backdrop of the case study is cognitive engineering, with its focus on supporting three levels of cognitive control, namely skill-, rules-, and knowledge-based control, respectively. In this design case study, the interface of the grid management system is divided into three hierarchical levels, each corresponding to a type of cognitive control. Details of the prototype system (the Compact System State Display) are introduced, as a reference to readers familiar with the particular challenges of designing energy management systems. The article also discusses the basic assumptions regarding human cognition and behaviour that engineers and designers might utilize in the design process, including the pros and cons of these assumptions.

Keywords*: Ecological psychology, abstraction hierarchy, cognitive work analysis, energy management systems*

Paper Received 05/09/2006; received in revised form 06/03/2008; accepted 22/10/2008.

1. Introduction

During the past decades, a lot of effort has gone into improving the human-machine system interface of nuclear reactor control rooms. In the same period, almost nothing has been done in order to systematically improve the human-machine system interface of grid control. Even though effort has been put into improving single aspects and subsystems (e.g. Mitsui & Christie, 1997; Mahadev & Christie, 1994; Sprenger, Stelzner, Schäfer, Verstege, & Schellstede, 1996; Kobayashi et al., 1996; Bacher, 1995), there has been no overall theoretical framework present to guide the design

Cite as:

Hoff, T., & Hauser, A. (2008). Applying a cognitive engineering approach to interface design of energy management system. *PychNology Journal, 6*(3), 321 – 345. Retrieved [month] [day], [year], from www.psychnology.org.

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process. In this paper we wish to introduce a cognitive engineering, or more precisely, an ecological approach to the design of energy management systems (EMS). In order to demonstrate how a unified EMS – system might look like if one take the theoretical position presented in this paper as the starting point, we introduce a compact system state display (CSSD). The article presents the CSSD system as a case study. This means that focus lies on presenting aspects of ecological interface design that might be useful for practitioners. At this point, we have not carried out research to empirically establish the extent to which this type of interface outperforms traditional interfaces. Also, the case study focuses primarily on the interface design as such, not on the social impacts for everyday work. For a discussion of social work implications of novel EMS interfaces, see Hoff (2004).

1.1 Mental models or ecological information?

It is common among developers of EMS – systems to state that the interface of the system should be compatible with the operator's mental model of that system. As traditional human factors and human-computer interaction are built on the reminiscence of the information processing approach, this comes as no surprise.

However, one can never be sure that the operators' mental model of the system is correct, in particular when the system in question is complex. Mental models are dynamic, and will change if the external events are not compatible with the current mental model. Hence, mental models can be incomplete or even plain wrong. Additionally, there is often no one correct mental model of a system – several mental models might be just as correct. To develop a true mental model of a Joint Cognitive System (JCS) will be far beyond the capabilities of the operator. This does not mean that we should not include user models in user interface design. Indeed, one need to model both the system as such, as well as the operator as an extended model of the system. For a detailed discussion of this, see Øvergård, Bjørkli and Hoff (submitted). But one need to differentiate between system and operator models, and the latter should not be used as the primary means of design. Vicente (1999) gives a detailed discussion of this fact, and states that "if workers are generally not aware of the deficiencies in their mental models, and if designers use these models as the basis for the interface design, then these deficiencies are almost sure to be transferred to the resulting interface" (p. 55).

During the past decade, the ecological approach has presented an alternative theoretical framework. The main difference between a cognitive and an ecological approach is that the cognitive, or information processing approach, states that cognitive phenomena such as perception, language, memory etc. are the result of information processing of discrete symbols (Fodor, 1983; Gardner, 1985). These symbols imply a representation of the real world in the head, whereas the ecological approach states that meaning can be perceived directly, without the need for such representations (Gibson, 1979; Michaels & Carello, 1981).

Cognitive constrains (memory limitations, speed of processing, attention, mental models etc.) and ecological constraints (the physical, social or cultural factors that shape human behaviour) contribute together and constitute the total action space. What is important is which of these should be given primacy to. Simon's (Vicente, 1995) parable about an ant on the beach gives a clue: "Viewed as a geometric figure, the ant's path is irregular, complex, hard to describe. But its complexity is really a complexity in the surface of the beach, not a complexity in the ant" (p.55). To understand and model human behaviour, we need to model the "beach", that is, all the factors that human behaviour is determined by, such as physical and social constraints. If one starts in the other end, one might erroneously conclude that the complexity of behaviour is something that belongs to the actor and not to the factors that shape such behaviour. Given this insight, work analysis has to start with the environmental constraints, not the cognitive ones.

Environmental constraints inherent in the system are descriptions of the existing possibilities for action, and are more a description of what actions that can be ruled out, rather than a prediction about behaviour per se. In process industry, there are always physical constraints that need to be respected in order to control the system. For EMS-systems such constraints might be e.g. minimum and maximum voltage level, frequency level, the amount of time deviation, outages in the grid, generator statics etc. Behaviour is also constrained at higher levels, e.g. the purpose for which the system was built or law regulations.

Rasmussen, Pejtersen, and Goodstein (1994) introduced the abstraction hierarchy as a means of representing the relevant ecological constraints in a psychologically significant manner for complex systems. The abstraction hierarchy differs from other types of hierarchies in that it is explicitly related to goals, because there is a means-end relation between the levels. Although the different levels describe the same system, every level has its unique set of terms, concepts and principles (Vicente & Rasmussen, 1992). The fact that inherent constraints are represented in a means-end relationship, knowledge of the system functioning will increase, because it is possible to move between the different levels. By moving up the hierarchy, the representations give a deeper understanding with respect to the overall system goals, whereas moving down the hierarchy the information becomes more detailed, and says something about how these goals can be achieved.

1.2 Control mode and the SRK-taxonomy

Rasmussen (1983) identified three levels of cognitive performance; the skill, rules and knowledge taxonomy. Knowledge-based behaviours are slow, serial, bottom-up activities, in which progress is made through processing performed at a structural level, i.e. on the basis of input of symbolic information, based on the operator’s mental model of the system. Skill- and rule-based behaviour on the other hand, is based on "perceptual processing", which refers to the fast, parallel and effortless thinking of normal activity. These heuristics are twofold: rule based behaviour represents if-then associations between perceptual cues in the environment and the procedures triggered by this cue, whereas skill-based behaviours "represents sensory-motor performance during acts or activities which, following a statement of an intention, takes place without conscious control as smooth, automated, and highly integrated patterns of behaviour" (p.258).

It is critical to note that complex and dynamic systems elicit all types of behaviours (i.e. skill-, rules- and knowledge based behaviour), depending on e.g. the time available for performing the operation, the available information at a certain time, and the amount of mental workload involved. Such factors are tightly coupled to the degree of control the operator experiences at a given time. Hollnagel and Woods (2005) have developed a contextual control model to describe how control constrains cognition, and suggests four different control modes: A scrambled control mode is characterized by zero control over the situation. Due to panic, actions are taken at random, and there is no rational reasoning or reflection involved. An opportunistic control mode is characterized by being determined by the salient features of the current context. There is little or no planning, because the context is not fully understood, or because the situation is chaotic. According to Hollnagel and Woods, the opportunistic control mode is a heuristic one that is applied when the constructs (knowledge) are inadequate, due to inexperience, lack of knowledge, or an unusual state of the environment. Hollnagel and Woods go on to state, rather worryingly, that many cases of controlled air carrier landings are carried out in this control mode. The tactical control mode is typical for cases in which the operator follows a known procedure or rule, but there is still little planning or reasoning involved. However, the operator's time horizon goes beyond what is currently critical. The strategic control mode corresponds to situations in which the operator has full control over the situation and is capable to make decisions based on higher-level goals, rather than salient features of the moment. The strategic control mode is of course the optimal mode for the operator, but this state of awareness is rare for operators of joint cognitive systems.

External disturbances affect the operator's experience of control and influence what control mode the operator operates within at a given time. The operator exhibits qualitatively different cognitive heuristics in different control modes, and the system should ideally accommodate these variations by supporting different cognitive heuristics, and not only the strategic control mode (which tend to be the case in most complex systems). It is of critical importance to design the decision support system in a way that makes it possible for the operator to deal with unanticipated events in a scrambled control mode.

1.3 Direct perception: Invariants in the optic flow field

Traditional EMS – systems gives the impression of supporting lower-level knowledge-based behaviour, because of the amount of detail in the information presented. However, in order to use this information efficiently, the operator needs to have a clear idea of the general system state. What is often the case is that when something suddenly goes wrong (as in the case of an outage) the operator is overwhelmed by alarms indicating that individual variables have reached set-point values. Even though this problem might be somewhat reduced by thorough advance off-line predictions of revisions and bottlenecks within the grid, there is a crying need for higher-level information that supports the operator in making predictions of grid behaviour, and subsequently supporting the operator in making better use of lower level information.

In searching for theoretical support for the construction of higher levels of information representation, it seems viable to attend to Marr's (1982) computational level (what there is to be processed), rather than to the algorithmic level, which is the main target of analysis in cognitive psychology. The reason for this is that we need an account of the type of information that operators actually use. In the words of Neisser, “if we do not have a good account of the information that perceivers are actually using, our hypothetical models of their information processing are almost sure to be wrong. If we do have such an account, however, such models may turn out to be almost unnecessary” (Neisser, 1987, pp. 11-24).

A thorough framework for describing the computational level is James Gibson's ecological approach to visual perception. Gibson (1979) states that there is no need for information processing of stimuli on the retina (much to the contrast of Marr, it should be said). In fact, perception is, in this perspective, not about stimulation at all, but rather the pickup of information from the optic flow field. To perceive something, the light has to be structured. The potential information that can be picked up, is invariant, that is, it provides a stable relation between the perceiver and the object. During evolution, humans have developed together with, and have adapted to this kind of invariant information. This approach is different from psychophysics (e.g. Fechner, 1860, 1966), because they chose to adopt Newtonian physics as the source of potential processable information. Gibson introduced ecological physics, which is information of higher order, i.e. invariant information scaled to human proportions and physiological makeup. For empirical findings, see Lee's (1993) Tau – paradigm, Carello and Turveys' inertia tensor – paradigm (Cooper, Carello & Turvey, 2000; Turvey, 1992), and Flach's (1990a) active psychophysics.

In Gibson's terms, we are lowered into a pool of potential information. What is lacking from graphical user interfaces however, are exactly the invariants the real world is full of. The situation is turned upside down; instead of detecting invariants, the designer has to artificially design invariants. This fact is both a problem and an advantage: Before the introduction of digitalized interfaces, analogue (mechanical) displays often conveyed information in adequate terms, whereas digital information removes most of the relevant semantic relations within the system. Consider Woods and Watts' (1997) description of the evolution of control centres. The old hardwired case represents a design that is directly visible in the layout of controls, displays, status panels and annunciators. In the digitalized control room, all you can see are the computer screens, but the actual complexity is hidden; behind what is actually shown, there are thousands of displays that could be called up depending on the context. In the previous designs, navigation involved moving physically around, touching the interface, and moving the head and eyes. The new trend of creating graphical user interfaces that forces the operator to statically navigate by means of menu options, in which all knowledge resides "in the head" of the operator, supports an information processing view of humans. This is because it triggers a knowledge based cognitive mode (Rasmussen, 1983), which is unnecessary as operators tend to favour a skill based cognitive mode. However, the common user interface design described above neglects the insights gained from ecological psychology, which states that a poor interface is one where ambiguities cannot be resolved by the activity of the observer, where assumptions, computations and inferences are required (Flach, 1995). From an ecological point of view, there is a need in order to design decision support systems for joint cognitive systems like EMS-systems to support online decision making, to show the intrinsic constraints by way of designing invariants which the operator can get attuned to (meaning that there are representations in the interface that the operator can act on, as opposed to information that depends on the operator to perform inferences based on the data. The ecological interface (EID) paradigm by Vicente and Rasmussen (1992) is one way of achieving this.

This general introduction has reflected some of the theoretical issues regarding interface design in complex systems today. We now move towards the more specific problem of how to design a new generation of interfaces for energy management systems. We do not believe that the present interface resolves all of the problems previously discussed. On the contrary, it should be looked at as an early attempt to change the focus of interface design within this domain.

2. EMS Interface Design

According to the introduction, the aim of our research presented in this paper is to extend existing representations by two additional display levels. The aim is to achieve a user interface that supports skill-, rule-, and knowledge-based behaviour. According to the control mode of the operator at any time, he/she can choose to switch between the different levels of interface representations. This will give the operator improved flexibility in problem solving activities, regardless of contextual variation and operator control mode. The three levels of representations will together constitute the CSSD. The well-known single-line diagrams (useful particularly at the knowledge based level in strategic operator control mode) are used at the bottom level of the CSSD.

2.1 The hierarchical approach

The top display level visualizes the global power system state and, therefore, includes a great amount of data. Hence, there is a low degree of information detail and a high data compression rate in this level. The main purpose of the top display level lies in the fact that it shows the operator whether the system is in a desired operating state or not. It shows the global system state and enables the operator to discern the global system state at a glance (what Woods and Watts (1997) has termed "the longshot"). Fig. 1 and 2 illustrates the hierarchical approach presented here.

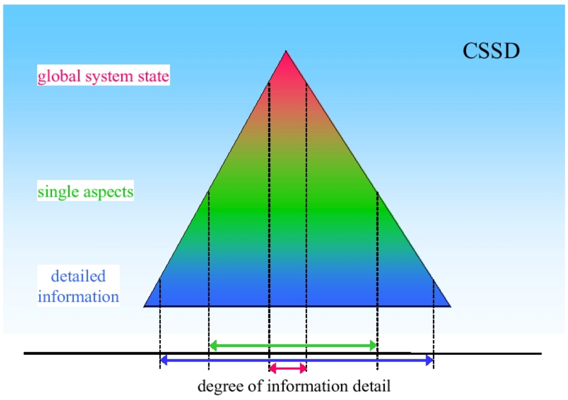

Figure 1. The hierarchical approach

Additionally it gives the operator – in case of a non-desired operating state – an idea about the amount of deviation from the desired operating state. It also gives the operator an indication of which aspects of the system state a deviation is found. This gives the operator a sense of direction, i.e. where to look next for further information. For this purpose the system state is subdivided into nine aspects. These are the bus voltage situation (BV), line flows (LF), results of contingency analysis (CA) and short circuit calculation (SC), interchange transactions (IT), optimal power flow (OPF), quality of load forecast (FOR), and state estimation (SE), as well as the state of interchange lines (IL). In general, these aspects show whether a desired state within an aspect is kept or not. For some aspects the desired state is defined through single desired values such as bus voltages that should be kept as a result of the OPF. For other aspects the desired state represents a situation with no off-limit conditions like line loadings smaller than a warning or overload level. All data related to these nine aspects are accessible at all three levels of information presentation. The idea, however, is to provide a 'longshot' display, where higher-order information is presented in a unified display. Detailed information about the aspects and their indices will be given in the paragraph regarding the numerical data compression.

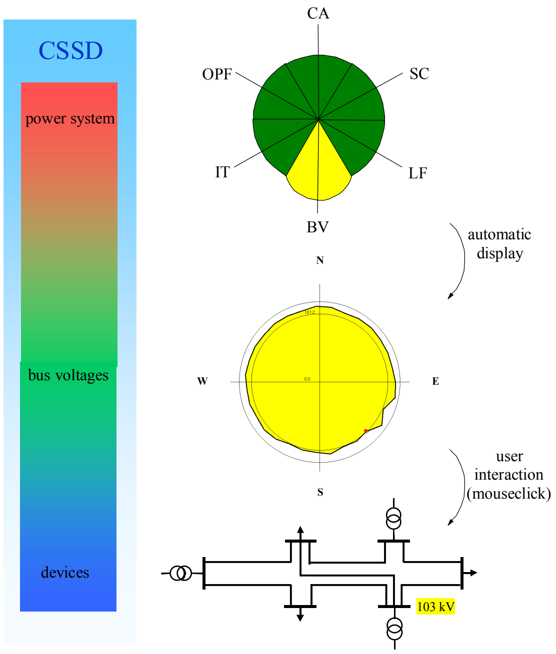

Figure 2. Hierarchical visualization system

An integral (highly compressed) display is used for the top level of the hierarchy in order to show all indices simultaneously. This is intended as an artificially designed invariant, which the operator will get attuned to during interaction with the system over prolonged periods of time. In the same manner, as in a natural environment, these invariants also give the operator a sense of direction in the evolving perceptual experience. The integral displays at the top level will be discussed together with graphical data compression methods.

The displays of the middle level are mainly used in case of a deviation from the desired system operating state. If the deviation is greater than a given value, the corresponding displays of the middle level will appear automatically. The operator can also request these displays manually. The main purpose of the displays in the middle level is to show the operator the essential and high-level information about relevant aspects of the system state mentioned above. This can also be achieved by using integral displays, which allow a certain kind of graphical data compression. Each display of the middle level visualizes one aspect of the power system state. Hence, there is a smaller amount of data included in the middle than in the top display level, and the degree of information detail is higher.

The operator uses the displays at the bottom level if he wants to consult detailed data regarding particular devices of the power system. The well-known and already used single-line diagram is an example of the displays in the bottom level, where the highest degree of information detail within the CSSD can be found.

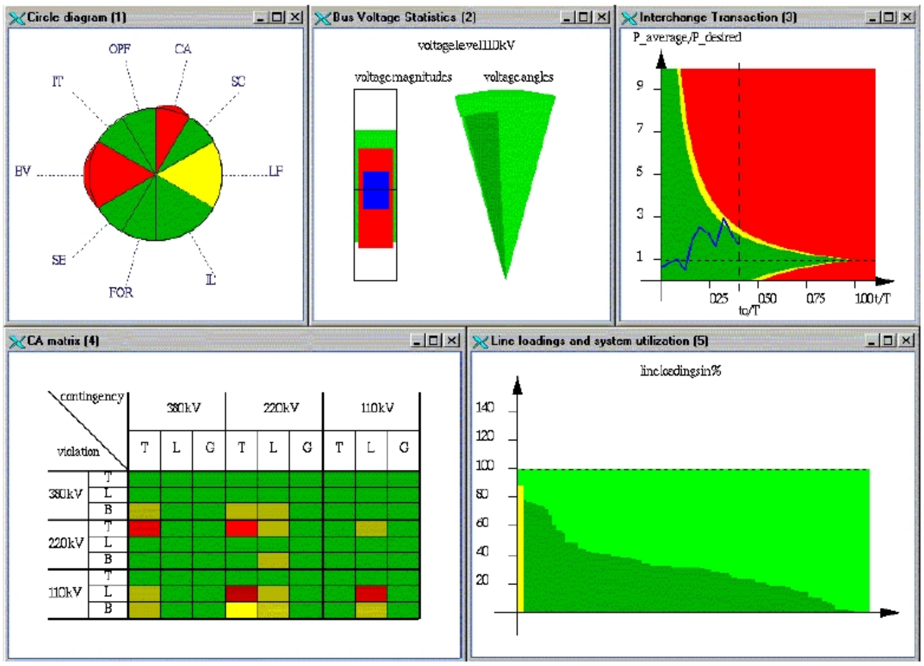

Figure 3. Examples from the hierarchical visualization system

Fig. 3 shows an example of the visualization system to get an idea of the applied approach. The global system state is visualized through a circle diagram in the top left hand side of fig. 3. The red circle segment for the BV aspect indicates some off-limit conditions which can be seen in the bus voltage statistics diagram of the 110 kV voltage level next to the circle diagram (top line, middle visualization). In the same way, off-limit conditions within the results of the CA are visualized through a smaller red circle segment and a matrix diagram. A warning condition within the LF aspect is indicated by a yellow circle segment and a yellow bar in the line loadings and system utilization diagram. Furthermore, this example shows a diagram for the state of a single interchange transaction. Some of the displays in fig. 3 are explained in detail below.

2.2 Numerical Data Compression

Numerical data compression methods are used in the top level of the CSSD to calculate the indices of the nine aspects of the system state. The crucial information at this abstraction level is the degree to which there are off-limit conditions. Additionally, the information should reflect how close the operating values are to their limits. The calculated indices must include all this information and must increase in an analogue fashion with advancing dangerousness of system deviations.

All indices of the CSSD can be interpreted in a similar way. An index of 1.0 stands for a desired state within the aspect of the system state, i.e. there are neither off-limit nor warning conditions and/or deviations from the desired values. The value of the index increases from 1.0 up to a given parameter value Kg if there are warning conditions, such as bus voltages near but within the limits or line loadings greater than a warning load level and/or deviations, e.g. between the past values of the load forecast and the actual load. If there is at least one off-limit condition and/or deviations greater than an acceptable amount, the index is equal or greater than Kg, and increases with more off-limit conditions and/or deviations.

The index OPF indicates whether or not the results of the OPF module of the EMS are kept. For this purpose the current operating state has to be compared with the one calculated by the OPF. The relevant information for the index OPF depends on the criteria used by the OPF module. E.g., active power losses for the current and optimal power flow as well as the cost of generation for both operating states are needed, if their minimization is used as OPF criterion.

$$OPF = 1 + \left(OPF_g - 1\right) \cdot \left[\frac{\sum_{i=1}^{n_K} w_i \cdot \frac{\left|K_{cur,i} - K_{opt,i}\right|}{K_{opt,i} \cdot A_i}}{\sum_{i=1}^{n_K} w_i} + \operatorname{sgn}\left(\sum_{i=1}^{n_K} B_i \right) \right] \quad (1)$$

with:

$$B_i = \begin{cases} 0 & ; \quad \left|K_{cur,i} - K_{opt,i}\right| < K_{opt,i} \cdot A_i \\ 1 & ; \quad \text{else} \end{cases} \quad (2)$$

OPF_g: index value if every criterion i has reached its acceptable normalised deviation A_i

n_K: number of criteria used for OPF

w_i: weight factor for each criterion

$K_{cur,i}$: current objective function value of criterion i

$K_{opt,i}$: optimal objective function value of criterion i

A_i: acceptable normalized deviation for criterion i

Thus, the index OPF is calculated according to (1) the normalized deviations of the current and the optimal objective function value of each criterion used for the OPF. The remaining indices are calculated in a similar way. For LF, the line loadings are taken into account if their values are greater than a given e.g. 80% threshold-parameter x_{thres}. Line loadings in the range of x_{thres} and an f. ex. 100% overload-parameter x_{over} are interpreted as warnings for those greater than x_{over} as overloads (Hauser & Verstege, 1999). The index BV is calculated out of normalized bus voltages using a desired value U_{des},I, upper $U_{up,i}$, and lower off-limit value $U_{low,i}$ for each bus i. Therefore, deviations from $U_{des,i}$ and violations of the permissible voltage range are included in this index (Hauser & Verstege, 1999). For the indices CA and SC, the number of off-limit conditions within the results of the security analysis is taken into account. A number of off-limit conditions less than a given acceptable number is interpreted as a warning and a greater number as an alert. The index FOR is calculated out of the normalized deviations of the past values of the load forecast and the actual load and, therefore, represents the quality of the load forecast. In a similar way, the results of the state estimation are used to calculate the index SE to indicate e.g. bad data. For the index IL, the free capacity of the interchange lines are taken into account, which have to be greater than a minimum value to ensure that there will be no overloaded interchange line in the case of a power plant outage. The index IT for the state of interchange transactions is calculated out of two normalized deviations for each transaction. The first deviation is built out of the running average power and its desired value which is given through the energy and time period of the contract. The second one is calculated out of the current power and its maximum and minimum limits. Therefore, the index IT describes the fulfilment of the interchange transactions regarding energy and power conditions of the contracts.

2.3 Graphical Data Compression

Graphical data compression methods are used in the top display level, as well as in the middle display level of the CSSD. Integral displays - a special kind of analogue visualization - are applied for this purpose. By "analogue information" we refer to the non-inferential nature of mechanical devices (for example the arms of a wrist watch) due to perceptual invariants as opposed to the inferential nature of numerical information (for example a digital/numeric wrist watch). Note also that such information is more than a differentiation in the level of detail; it is also possible to represent relations at a different level of description that cannot be reduced to an atomistic level of representation.

High-level information is defined here as the relationship of single values either with each other or with a desired value. They serve mainly as a basis for showing the operator the next step regarding system operation. Examples of high-level information are "heavy power flows from west to east of the supply system", "balanced voltage profile", and "power system in a desired state".

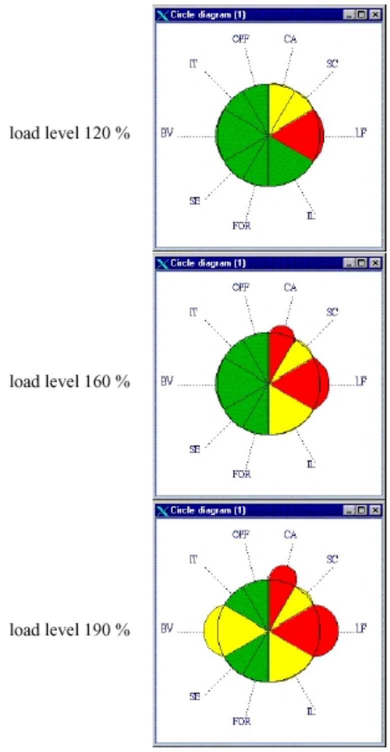

Figure 4. Circle diagram for global system state

One example of an integral display in the top display level of the CSSD is the circle diagram, which is shown for three different load levels in fig. 4. In this circle diagram, geometric shapes are used to represent operating states within several aspects of the system state. A segment of the circle and an axis for the corresponding index is used for each aspect. The colour of a segment shows the operator whether there are neither warnings nor alerts (green), at least one warning but no alert (yellow), or at least one alert and maybe warnings (red) in an aspect of the system state.

The distortion (deformation) of each segment of the circle is proportional to the corresponding index value. Therefore, it is a qualitative indicator of the deviation in the aspects of the system state. The aspects BV, LF, and IL are represented with bigger segments of the circle due to their higher importance for the operator (fig. 4). Thus, the influence of these three aspects, on the impression of the whole diagram regarding the global system state, is higher than any one of the other aspects. If all indices have their desired values of 1.0, the diagram will show a green coloured circle. Otherwise, a diagram with distorted and yellow, and/or red coloured segments appears in order to indicate deviations from desired values. The distortion and the portions of green, yellow, and red of the whole diagram represents the deviation of the global system state from the desired system state. The circle diagram represents, in a straightforward way, what we mean by "invariant information", and "analogue visualization". Once the operator has established an association between the represented (the nine subdivisions) and its representation (the circle diagram), he/she is able to directly infer the system status by reference to the geometric symmetry of the figure. Integral displays are also used in the middle display level, and some of the most important displays are presented next.

2.4 Mid-level displays, geographical information

The global power system state can be visualized through the circle diagram with indices for nine aspects of the system state, as mentioned above. Therefore, deviations within the power system state can be assigned to the corresponding indices and aspects respectively. But there are no geographical information passed on to the operator that may help him/her to quickly find places of warnings and/or alerts within the grid. For this purpose, the iso-line diagram in fig. 5 as additional display for the global power system state with included geographical information, has been developed. An iso-line diagram is a 2-dimensional representation of a 3-dimensional surface, which contains a given set of vertices (Hauser & Verstege, 1999). The vertices used for the iso-line diagram in fig. 5 are indices that describe the state of devices in the network, such as bus bars and lines at their geographical place. Since lines cannot be described by only one geographical place, the centre of the beginning and the end of a line is used in this diagram. The calculation of the indices is done similar to the one of the indices in the circle diagram, but includes only the data of the corresponding device (Hauser & Verstege, 1999; Hauser, 1999). Places of devices with neither warnings nor alerts are represented by a green colour, those with at least one warning but no alert by yellow colours, and those with at least one alert, and maybe some warnings by red colours, respectively. Therefore, geographical regions with their corresponding system state can be easily discerned.

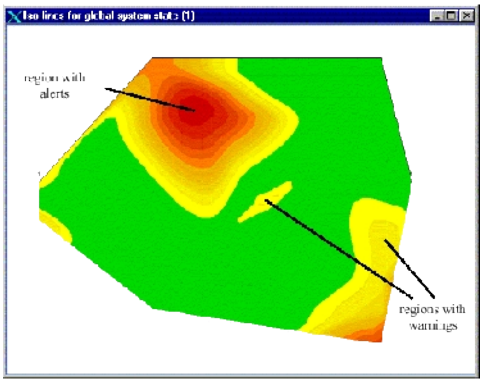

Figure 5. Iso-lines for global system state with geographical information

2.5 Other aspects of the system state

Several integral displays are used in the middle display level of the CSSD to show the essential and high level information about aspects of the system state. These are e.g. the matrix diagram for the results of the contingency analysis and the bar diagram for line loadings and system utilization, which are shown in fig. 3 and explained in Hauser and Verstege (1999), Hauser (1999). A similar bar diagram for free line and system capacities is shown in fig. 6. The bars representing the lines of the network are sorted according to their free line capacities in MVA. The lowest bar in the diagram shows the minimum possible load increase if there are no current overloads. In case of current overloads, they are shown as negative free line capacities, visualized with red bars in the diagram. In this case, a minimum possible load increase cannot be given without taking detailed information into account, e.g. the place of injection and take-over of a transit and the resulting load flow situation. The structure of the whole diagram and the distribution of the bars in the diagram give an idea of free capacity within the power system.

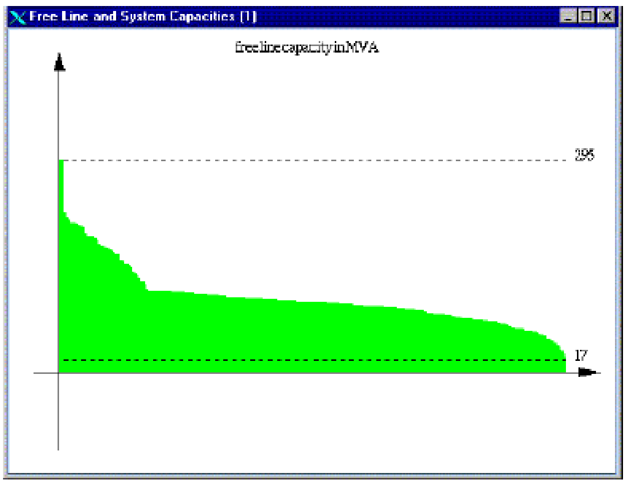

Figure 6. Free line and system capacities

Figure 7 shows an example display with runny colours for visualizing line flows and their changes due to a transit of 100 MW. The width of the runny colour bars represents the amount of active power that flows from the lower towards the upper colour saturation of the bars. The green part of the bars represents the active power flows without the transit, and the turquoise one represents the changes as a result of the transit. The turquoise part will surround the green one if there is an increased active line flow. There is a vice versa situation in case of a decreased active power flow. Furthermore, generation centres are indicated with node's surroundings of low color saturation and load centres with high colour saturation. With this kind of visualization the effect of transits on the line flow situation can be seen easily.

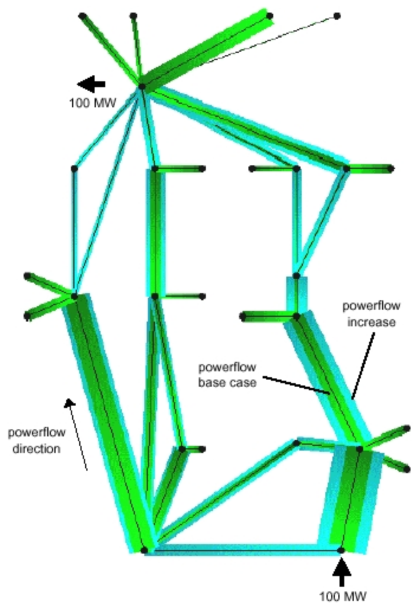

Figure 7. Line flows represented with runny colours

The state of interchange transactions can be visualized through the diagram in fig. 8. The diagram has three coloured areas, green, yellow and red. It shows the running average power from the beginning of the interchange transaction until the current moment. The fulfilment of the transaction at the end of the contract period is only possible if the average power remains in the green or yellow area of the diagram. If it reaches red at least once, the transaction cannot be fulfilled regardless of further energy interchange. The yellow area represents a warning level to indicate a potential violation of the interchange contract.

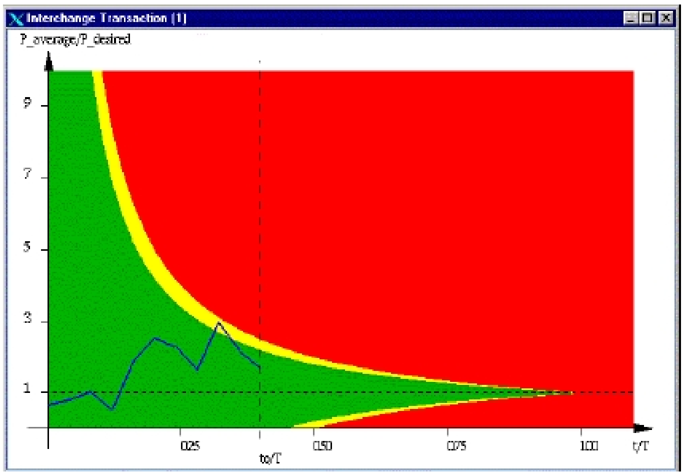

Figure 8. State of interchange transaction

In fig. 9 the bus voltage situation for two voltage levels is shown through two different display types.

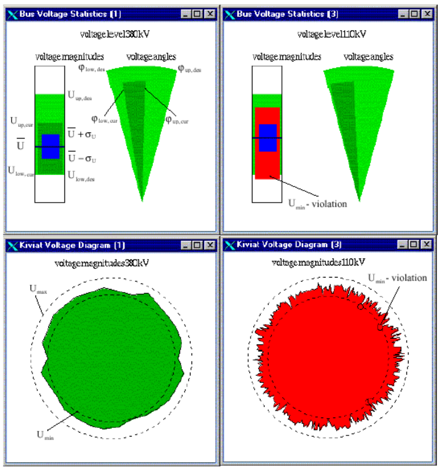

Figure 9. Displays for bus voltage situation

The first display type in the top of fig. 9 visualizes statistical values of the bus voltage magnitudes and angles. The statistical values of the voltage magnitudes are the mean value, standard deviation as well as the current and desired upper and lower bus voltage magnitude. With this kind of display, it is easy to see the balance of the voltage profile as it is indicated through the range of the standard deviation around the mean value. The current voltage range and the closeness to the off-limit values can easily be seen as well. For the bus voltage angles only the current and desired upper and lower values are shown because they can be used as an indicator for the amount of active line flows and system stability. The Kiviat diagrams in the bottom of fig. 9 show the bus voltage magnitudes, their minimum and maximum limits as well as limit violations. It is easy both to get an idea about the voltage profile and also to discern limit violations with this kind of display.

3. Discussion

The belief that system safety can be improved by post hoc analysis of human error (which accounts for about 80% of all major accidents) and subsequently correcting the one factor that led to that accident rests on the assumption that operators can, and do, follow normative instructions of how to perform work, and that it is possible to predict up front how the operator might behave in certain situations. This is a problem of confusing hindsight with foresight. In retrospect it is always possible to find violations to certain procedures and to conclude that this causally led to the accident. When one looks in the microscope, and study human behaviour in situ, one finds that even for highly constrained tasks, operators tend to adjust their actions in order to adapt to the requirements put forth by the particular context at hand (Hutchins, 1995; Woods, 1996; Vicente & Burns 1996). For joint cognitive systems like the operation of electrical power systems one cannot predict operator behaviour, because a) the initial conditions will vary, b) there is often more than one correct strategy for solving a particular problem (different operators might use different strategies, or one operator might use different strategies at different times), and c) unforeseen disturbances require compensatory action (Vicente, 1999). Control theory has shown in formal mathematical models that operator behaviour cannot be predicted as long as the system has one or several of these characteristics (Flach, 1990a). The implications of these facts are that behaviour actually needs to vary in order to keep the outcome constant.

In chaotic systems (Kelso, 1995; Thelen & Smith, 1995), the one variable that causes a behavioural phase shift (the control parameter), cannot be predicted. What cause a phase shift are the perturbations in the dynamic system, not in the control parameter per se. Given this fact, there is no meaning in improving a system by changing the one cause that led to the accident. On the contrary, the fundamental design issue is, according to Rasmussen (1999), not to fight individual causes of human error but to create a work environment for operators that make the boundaries to failure visible and reversible.

For joint cognitive systems, one of the main design challenges is to support the operator when rare and unanticipated events occur. It is under these situations that major accidents tend to happen (Perrow, 1984). Because neither operator behaviour nor system variation can be predicted, it becomes difficult to use traditional approaches to system design. Normative approaches, e.g. task analysis (Kirwan & Aintsworth, 1992), tend to focus on "the one best way" of performing work, that is, how the system should behave. These tayloristic approaches suffer from the fact that they cannot accommodate unanticipated events. The moment an event occurs that the system was not designed for, the operator is left unaided. Thus, such systems provide the least information at the one critical point where it is needed the most.

Phenomenological approaches have, much in the same manner as the ecological approach, evolved as a reaction to the notion that human behaviour is characterised by logic reasoning based on information processing of discrete symbols (Newell & Simon, 1972; Churchland, 1996). Characteristic of descriptive approaches is to study cognitive phenomena as they happen in real-life situations. Important contributions have been made in the study of expertise (Dreyfus & Dreyfus, 1986), navigation (Hutchins, 1995), decision making (Klein, Orasano, Calderwood & Zsambok, 1997) and problem solving (Rasmussen, 1974). Although these contributions have had a significant influence in fundamentally changing the perspective of how cognition should be studied, the practical implications of such an approach within human-machine systems research remains somewhat unclear. The field that most explicitly uses a descriptive approach to system design, is Russian activity theory (Nardi, 1996; Bødker, 1990). Nardi (1996; Vicente, 1999) states that activity theory is more of a descriptive tool rather than a strongly predictive theory.

The user-centred design tradition (e.g. scenario-based design, rapid prototyping and usability testing), might also be considered descriptive, as it takes contextual observations of the users as its starting point. Although it is a very appropriate tool for systems of low to medium complexity, they are of limited value when it comes to the design of joint cognitive systems. The reason is that current practice depends on the devices the operators have available to them. That is, there are many currently unexplored possibilities of performing work (for a detailed discussion of this, see Vicente, 1999). Because people adapt their behaviour in order to meet even the slightest change in variation, the introduction of new features based on existing devices leads to new ways of interacting with the system. Hence, the task-artefact cycle (Carroll, 1991) weakens user-centred design as an omnipotent tool for complex systems.

It follows from this discussion that what the designers need in order to support the operator of EMS-systems is not a prescription of how they should behave in certain situations, or just a description of how the operators actually behave. On the contrary, what is needed is a system that is flexible enough to accommodate variations both in operator behaviour and in the system itself, which is not based on current practice. This can be achieved by identifying the relevant constraints of the system, and to represent these constraints in a way that is compatible with human cognition. This is what Vicente (1999) has termed a formative approach to system design.

We have, with the development of the CSSD – system, not carried out an ideal predictive cognitive work analysis, and it is not clear to us what such an ideal process should look like. The main challenge is, that in practical product development (as opposed to the micro-worlds of science), it is almost impossible to gather a project group that both understands the principles of the ecological approach, as well as understands the basic functioning of the system, at a time when no presumptions of the interface or the operators have been made. Although neat in theory, the ideal prescriptive approach difficult to carry out.

What we have done, however, is to ensure that ecological (body based) information is represented in the interface, and ensured that a hierarchic display of information is readily accessible. Depending on the operator's current overview of the situation (the degree of cognitive control), he/she can access information at several layers, and assist the operator in regaining cognitive control. Additionally, the visual displays represent the constraints (boundaries) of the system, rather than as serial information. Constraint based information empowers the operator, because he/she can act flexible in the face of external disturbances, rather than being a passive agent that carries out stepwise if-then corrections. This is what differentiates predictive from normative approaches.

4. Conclusion

In the development of the CSSD, we have explicitly aimed at exploiting theoretical advances in the field of ecological psychology, particularly with respect to Rasmussen's

Skill-, Rules- and Knowledge-based model. Traditional EMS tend to be based on a low level conception of human cognitive functioning; that is, the conception that humans process information from the bottom up, on the basis of the basic structural elements of the thought process. Traditional displays, such as the single-line diagrams, taps a task humans are not very good at – namely to perform pure mental inferences, in this context in order to derive a conclusion about the total system state. Being extremely mentally laborious, this task leaves no mental space for the task human operators are very good at; namely to solve problems at hand by creative adaptation based on years of experience with similar cases (so called context conditioned variability).

It can be argued, from an ecological point of view, that what is lacking in traditional displays are the invariants which we are perceptually attuned to during hundred thousands of years of co evolution between the organism and the environment that surrounds it. In Gibson's (1979) terms, we do not perceive the world by mentally reconstructing it. Rather, we are able to directly pick up information, because the information is already structured in invariant ways. For visual perception, the invariant arise because the light travels in fixed angles. For instance, when you move your head to the right, the perceptual world moves in the opposite direction. All perceptual experiences are perceived as being continuous; there are no pauses or leaps in the stream of information. This is not because the brain is a fast processor, reconstructing retinal snapshots in a rapid fashion, making it look as though the information is continuous. Rather it is continuous because our senses are tuned by way of evolution to pick up certain kinds of invariant information in the optical (or perceptual) flow field.

In the process of developing the CSSD we have pursued the task of creating such invariants, because no invariants can exist in a virtual medium without having graphically recreated them (mimicking the invariants of the real world). There is, according to Woods (1997), "…nothing inherent in the computer medium that constrains the relationship between things represented and their representations".

We have constrained the relationship between the represented and its representation by adding two more levels of abstraction to the traditional displays. They both contain information that cannot be directly perceived from low level displays. All the displays at the two top levels carry invariant information, as the graphical displays vary their shape and colour in an invariant relation to what happens "out there" in the world of power flow patterns and their changes, transits, interchange transactions and their fulfilment, loads and generations, system utilization, and results of the security analysis describing the global system state.

In this sense, we have attempted to support the online problem solving activity of the operator by moving the quality of the interaction on a indirectness to directness continuum, e.g. from effortful serial processing of discrete variables to ecological pick-up of direct information conveyed by the graphical interface. In Rasmussen's (1983) terms, we have moved from tapping knowledge-based knowledge to tapping skill-based knowledge.

To represent as many relevant constraints as possible, and to represent these in a way that support skill-, rules-, and knowledge behaviour, is the only way we see it possible to support the operator when rare and unanticipated events occur. Because these events cannot be predicted, one can do nothing but to represent the information available in a sensible manner. For the rest of the job, one has to rely on the expertise of the operator.

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