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NUMERICAL MODELS IN REPRESENTATION DESIGN: COMPUTING SEAWATER PROPERTIES IN AN ECOLOGICAL INTERFACE

Nathan Lau
Greg A. Jamieson
Cognitive Engineering Laboratory, University of Toronto
Toronto, Ontario, Canada

The contribution of cognitive engineering in complex systems is often limited by the availability of information to populate advanced representational forms, such as those characterized by the Ecological Interface Design framework. We suggest the application of numerical models to derive required information, supplementing the analytical methods that are commonly used in computational aiding. We demonstrate the approach by presenting a solution combining numerical and analytical methods to the problem of determining seawater properties in a nuclear power plant. The example demonstrates that numerical approaches can expand the range of possible applications of representation aiding in complex systems.

INTRODUCTION

The nature of work in complex systems is becoming increasingly knowledge-based as well-defined and frequently occurring tasks are automated, leaving ill-defined problems and unanticipated events for the operators to manage. As a result, today's operators face challenges associated primarily with monitoring and problem solving. This aspect of work can be supported by human–machine interfaces that provide effective representations of domain constraints that enhance monitoring and diagnostic performance (Woods, 1991; Vicente & Rasmussen, 1992).

The development of interfaces usually involves two generic stages – analysis and design (Figure 1). The analysis generates requirements while design translates the requirements into perceivable representations. However, some requirements specify parameters that cannot be measured due to limitations in either instrumentation availability or capabilities (see, e.g., Reising & Sanderson, 2004; Maddox, 1996). Reising and Sanderson (2004) investigated the impact of instrumentation availability in a simulator study. They find a main effect of instrumentation and an interaction effect between interface design type and instrumentation availability. The study showed that an ecological interface for a pasteurizer simulator was superior with maximum instrumentation but inferior with minimal instrumentation compared to a mimic representation. These empirical results caution designers to be cognizant of the fact that the effectiveness of representational forms is dependent on the connection between instrumentation availability and design frameworks (i.e. combinations of specific analysis and design concepts).

The other limitation is the inability of instrumentation to measure higher-order information. In some such cases, the parameter in question can be derived from sensed data. For example, energy transfer in a heat exchanger cannot be measured directly, but it can be derived from measures of temperature and flow rate given values for the densities and specific heats of the fluids and the first law of thermodynamics. This is an example of computational aiding using an analytical method - the approach that underlies much of the literature on configural displays. However, as the complexity of the modeled domain increases (e.g., when fluid properties vary with environmental conditions), it becomes increasingly difficult, if not impossible, to obtain analytical solutions. In such cases, the representation designer might conclude that some requirements simply cannot be satisfied in practice even if there is an effective representation. Thus, the ability to obtain information on physical processes limits the potential contribution of both analyses and representation aids to complex systems.

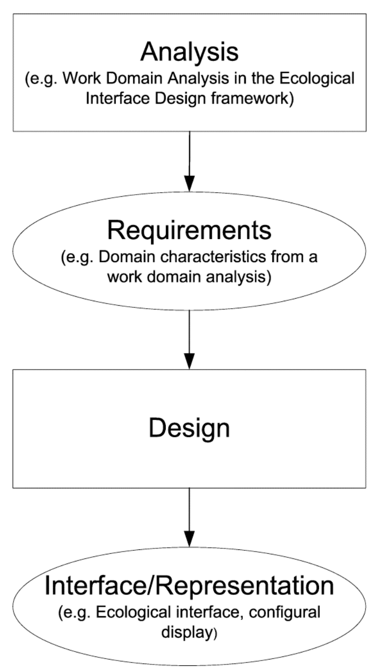

Figure 1: Generic stages and products of interface development.

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Numerical methods are being increasingly applied in the engineering sciences to construct computational models where analytical methods have proven insufficient. Numerical methods apply algorithms to obtain approximate answers to mathematical problems that do not have closed-form solutions. These methods include curve fitting, interpolation, and non-linear differential equations. Numerical models can be found in many applications ranging from computational fluid dynamics to weather forecasting. Despite the possibilities afforded by numerical methods, they have not been exploited in the design of representational forms. This article demonstrates, through an example, how numerical methods can resolve the limitations of both sensors and analytical methods in providing the necessary information to populate representational forms. If successful, such methods could expand the range of domains in which advanced representational aids can be applied.

PRACTICE INNOVATION

To provide an example of the application of numerical models in satisfying information requirements for representational forms, we discuss a graphical element drawn from an ecological interface for the condenser subsystems of a Swedish boiling water reactor plant simulator (Lau and Jamieson, in press).

The information requirements

A Work Domain Analysis (WDA; Rasmussen, 1985) of the condenser subsystems specified the domain characteristics and constraints which became the information requirements for designing the ecological interface. A critical process indicated by the WDA is the condensation of the turbine exhaust steam into condensate for the feedwater subsystems. The process of condensation is achieved by transferring heat from the exhaust steam (the energy source) to the seawater (the energy sink) in the condenser. A key domain constraint for plant stability is thus a condensation process involving an energy loss from the steam that is equal to the energy gain to the seawater. Information requirements extracted from the WDA include: (a) energy lost by the steam, (b) energy gained by the seawater, and (c) the relationship that (a) and (b) should be equal.

The representational form solution

The generic graphical solution to show that two variables should be equal is a connected bar graph (Burns and Hajdukiewicz, 2004, pp. 63). Figure 2 shows an ecological form for the energy balance in the condenser. The bar at left represents the heat loss from steam and the right bar represents heat gained by seawater. The line connecting the two bar graphs forms an emergent feature that conveys the balance between these energy levels.

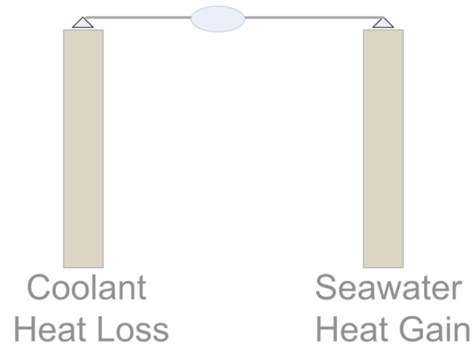

Figure 2: Graphical form in the ecological interface for the condenser energy balance.

The benefits of the energy balance graphical element are threefold. First, it provides an unambiguous indicator of the stability of the condensation process in thermodynamic terms as compared to single parameter representations, which must be interpreted in conjunction with other parameters. This relieves the operators of the arithmetic processing involved in integrating several variables, an example of Knowledge Based Behavior – which is effortful and error-prone (Rasmussen, 1983). Second, the energy balance differentiates normal (balanced) from abnormal (imbalanced) states of the process in a salient manner, thereby facilitating early detection of deviations from expected conditions. Third, the energy balance can indicate changes in heat transfer efficiency. A *temporary* energy imbalance depicts a transient state of the plant that typically affects cooling and efficiency. For instance, if seawater temperature increases, resulting in a decrease in heat transfer efficiency, the bar graph representing the energy gained by the seawater will decrease first, resulting in an energy imbalance (Figure 3). On other hand, if the temperature of the exhaust steam from the turbine increases, the reverse occurs.

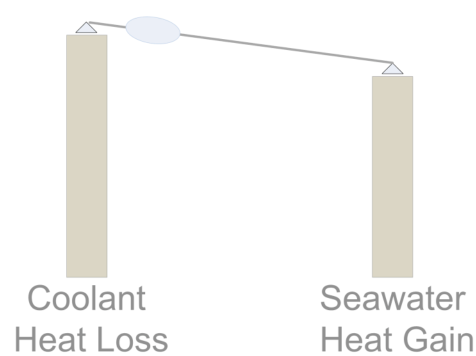

Figure 3: Energy loss from the coolant is not equal to energy gained by the seawater.

THE PROBLEM

The energy balance graphical form is simple and familiar to many interface designers. The engineering challenge lies in determining the amount of energy transfer at both the source and the sink to fulfill the requirements specified by the WDA. For the purposes of this example, we will focus on the bar graph at right, which represents the heat gain of the seawater. Energy cannot be sensed directly; therefore, it must be computed from sensed data and values for the specific heat and density (5). In cases where the environmental conditions for the fluid are stable, the specific heat and density can be treated as constants. This would constitute an analytical solution to the problem of determining the energy gained by the seawater. However, seawater varies in salinity, temperature, and pressure depending on environmental conditions, resulting in a range of specific heat and density values. These variations affect the heat transfer in the condenser such that an analytical solution based on constant values would not reflect the true heat gain of the seawater. The operator would thus be unable to assess whether the energy balance is being maintained.

THE NUMERICAL METHOD

We applied numerical models of seawater (Fofonoff & Millard, 1983) to derive the information specified by the WDA and populate the representational form. A complete, hybrid formulation for calculating energy gained by seawater is presented to exemplify how numerical methods can complement analytical methods.

Table 1 denotes the relevant variables:

Table 1: Notations of variables.

Parameter	Notation
Energy	E
Enthalpy	H
Mass	m
Volume	v
Temperature	T
Pressure	P
Water Density	ρ
Numerical Method of Water Density by Fofonoff and Millard (1983)	SVAN
Specific Heat of Seawater	C_p
Numerical Method of Specific Heat by Fofonoff and Millard (1983)	CPSW

The information of interest is energy gained by seawater from the inlet to the outlet of the condenser:

$$\Delta E = E_{outlet} - E_{inlet} \tag{1}$$

Since energy cannot be directly sensed, it is expressed in terms of mass and enthalpy:

$$E = m \times H \tag{2}$$

Typically, instruments in process control are either designed or limited to measuring volumetric flow rate and temperature as opposed to mass and enthalpy of a fluid. Hence, mass is expressed in terms of volume and density, and enthalpy in terms of temperature and heat capacity:

$$m = v \times \rho \tag{3}$$

$$H = T \times C_p \tag{4}$$

Equation (2), energy, can then be expressed as:

$$E = v \times \rho \times T \times C_p \tag{5}$$

Substituting for the terms in Equation (1), the analytical solution of energy gained by seawater *in a stable environment* can be expressed by three measured parameters and two constants:

$$\Delta E = v \times \rho \times C_p \times \left(T_{outlet} - T_{inlet}\right) \tag{6}$$

However, density, ρ, and specific heat, C_p, of seawater are not constants under varying environmental conditions; thus, the analytical solution - (6) - would not accurately reflect the energy gained by the seawater. We therefore turned to numerical models to obtain approximations of specific heat and density that account for environmental conditions, thereby improving the accuracy of the analytical solution.

Fofonoff and Millard (1983) described and coded a set of nine algorithms to calculate seawater properties. Two algorithms – specific heat of seawater (CPSW) and specific volume anomaly and density anomaly of seawater (SVAN) – can be used to determine the energy gained by the seawater. The CPSW algorithm is a polynomial estimation of the integral that approximates specific heat; whereas the SVAN algorithm is a set of functions derived from curve fitting to a set of empirical data that approximate specific density. Both SVAN and CPSW are numerical functions of temperature, salinity, and pressure of the seawater. Salinity and temperature need to be measured by instruments, whereas pressure is pre-determined based on pump specifications/characteristics for this particular power plant system. Density and specific heat are thus expressed as:

$$\rho = SVAN(T, s, p) \tag{7}$$

$$C_p = CPSW(T, s, p) \tag{8}$$

The final solution for calculating energy gained by seawater can now be expressed with parameters that can either be computed or measured:

$$\begin{aligned} \Delta E &= E_{outlet} - E_{inlet} \\ &= \left[v_{inlet} \times (SVAN(t,s,p)_{outlet} \times CPSW(t,s,p)_{outlet} \times T_{outlet}\right] \\ &- \left[v_{outlet} \times (SVAN(t,s,p)_{inlet} \times CPSW(t,s,p)_{inlet} \times T_{inlet}\right] \end{aligned} \tag{9}$$

By applying the algorithms to determine seawater properties, the energy gained by seawater in the condenser under varying environmental conditions can be computed.

DISCUSSION

The numerical model for seawater properties helps to fulfill the information requirements identified by the work domain analysis, thereby enabling a visualization of the energy balance between the feedwater and the seawater across the full range of the condenser's operating conditions. Such a solution could not be provided through sensed values and analytical derivation alone. In fact, some sensed parameters by themselves, such as salinities, are not practically useful to operators but critical to the numerical model for seawater to derive higher-order information (c.f., Maddox, 1996). Thus, were the designer to neglect numerical models in obtaining the necessary information to fulfill the requirements and populate the interface, the energy balance display could not be implemented. Numerical models can play the same role for other interface or representational forms in fulfilling the information requirements specified by the cognitive analysis.

The application of numerical models is, nevertheless, confronted with practical challenges. It is unlikely that a numerical model exists for every parameter of interest. Development of numerical models usually requires an extensive amount of research; thus, building numerical models as needed is probably not very practical. Even when they are available or developed, numerical models often specify their own sets of information requirements that demand additional sensors. Evaluation and validation of numerical models also tend to be difficult as they are based on empirical data rather than abstract relations or established scientific findings as in analytical methods. Numerical models are usually composed of complex mathematical expressions that may be time-consuming to implement. The cost to obtain the process information remains high, even though information availability is expanded through numerical methods.

As with any other method, the application of numerical models to derive additional information also needs to demonstrate a clear return on investment. Reising and Sanderson (2002, 2004) have developed the "sensor abstraction hierarchy" to examine the implications of sensor availability in a qualitative manner for ecological interfaces. The sensor abstraction hierarchy can also serve to assess the benefits of sensed or derived information. Information availability analysis tools, if not available, should be developed for other interface design frameworks. The results of such analyses could serve as supports for adding the new information derived from numerical models. However, further research is necessary to determine the costs and benefits of numerical models. Methods and empirical data to quantitatively justify the cost of added information from installing of new sensors and/or implementing complex algorithms are not available. The costs of implementation and maintenance may be trivial in comparison to the continuous benefits enjoyed during monitoring and diagnoses. The cost-benefit trade off of adding information deserves more attention in research to assist interface designers in making informed decisions on representational forms.

The development of the energy balance graphical element in an ecological interface for the condenser subsystems revealed that numerical models can be practically applied in industrial settings to fulfill information requirements and support representational forms. While the cost-benefit trade off of using numerical methods in this way requires further research, numerical models have been demonstrated here to make information available that cannot be achieved by instrumentation and analytical methods alone. Thus, broader application of such models could facilitate the adoption of representation aiding, ultimately improving monitoring and diagnosis performance in complex systems.

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