COMPARISON OF INFORMATION REQUIREMENTS FROM TASK- AND SYSTEM-BASED WORK ANALYSES

Greg A. Jamieson
Cognitive Engineering Laboratory
Department of Mechanical & Industrial Engineering
University of Toronto
jamieson@mie.utoronto.ca

Cognitive engineers commonly use either system-based or task-based analysis methods to identify information content requirements for system design. However, relatively little is known about the relationship between these two classes of methods. This article provides a comparison of the requirements generated by one system-based analysis and two task-analyses in designing an interface for a complex production process. A comparison of the requirements identified by each analysis revealed that, while there was a substantial overlap between them, the two classes of methods produced largely complementary information. Further analysis revealed that the existing instrumentation system in the plant was not sufficient to support many of the content requirements, and that this limited the effectiveness of the existing interface. These findings yield important implications for the design of complex human-machine systems.

INTRODUCTION

Methods of Content Specification

Ecological Interface Design (EID) aims to provide support for effective management of unanticipated events in large-scale systems (Vicente & Rasmussen, 1992). Over the past decade, the framework has been applied to increasingly more challenging design problems and across a range of domains (see Vicente, 2002, for a review). A key foundation for providing this support lies in the systematic identification of the information requirements (IRs) that guide system design. In EID, this takes place through the abstraction hierarchy (AH; Rasmussen, 1985) framework, producing a system-based analysis that describes the physical and functional constraint space that governs opportunities for operator behavior.

Other approaches to human-centred systems design employ task-based methods for the identification of IRs. These approaches rely upon descriptions of tasks carried out during normal operations and during planned-for abnormal operations. The potential drawback of task-based approaches is that it is impossible to predict all possible events. Thus, the designer risks leaving the operator with incomplete support at the worst possible moment. In contrast, an argument can be made that EID, with its primary emphasis on system analysis, fails to exploit the wealth of knowledge embedded in expert task performance under anticipated operational conditions.

This article describes one aspect of a larger effort to explore the integration of task-based and system-based methods for the identification of IRs. Through analyses of a small-scale system, Miller and Vicente (2001) showed that there were substantial benefits to be gained by viewing the two types of approaches as being complementary rather than competing. Miller and Vicente (1998, 1999) extended their work to a moderately complex, real-world petrochemical production process, making similar observations about the complementarity of the approaches. However, these analyses were limited in that the information requirements were not compared in any systematic way, integrated, or used to design an interface.

Information Requirements

An information requirement (IR) is a statement of a specific piece of information or relationship that must be incorporated into an interface intended to support effective control of a target process. It is assumed that a comprehensive set of IRs forms a *necessary* body of information for this task. The aim of integrating both task- and system-based analysis methods can be cast as an effort to move closer to identifying a *sufficient* set of information requirements that, if met in an operational information system, would allow for effective adaptation under the broadest range of events.

A consistent observation made by designers employing EID is that the AH analysis often identifies a set of IRs that exceeds the information resources provided by contemporary instrumentation systems (Dinadis, 1997; Jamieson & Vicente, 2001; Reising and Sanderson, 2002). This poses an important question when we consider integrating system-based approaches with task-based approaches. If the IRs produced by task-based approaches are indeed complementary to the IRs produced by system-based approaches, then it is necessary to examine whether these additional requirements are supported by existing instrumentation systems. The results of that examination will have a substantial impact on system design.

This article presents a comparison of the IRs identified by a system-based analysis and two task-based analyses. It further examines the extent to which these requirements appear in the current interface and whether they are supported by the contemporary instrumentation system. Details on the analyses themselves and the process of compiling the IRs can be found in Jamieson (2002a).

Target Process and Analysis Tools

The target system for this analysis is an acetylene hydrogenation reactor (AHR), a sub-system of an ethylene refining process. The AHR is a moderately complex work domain; however, it is arguably the most critical part of the process (Miller & Vicente, 1998).

A series of analyses were performed on the AHR. First, a system-based analysis was performed using the abstraction hierarchy and a set of information requirements was generated (Miller & Vicente, 1998). The abstraction hierarchy is a two-dimensional hierarchical modeling framework that supports system-based analysis. The two dimensions are the means-ends and part-whole hierarchies. Moving through the five levels of abstraction parallels a move from more concrete descriptions of the system to more abstract descriptions, although each description is complete at its given level. Similarly, moving through the levels of aggregation parallels a move from a component-wise description of the system to a description of the system as a whole unit. Taken together, the two dimensions describe a physical and functional constraint space that governs opportunities for operator behavior.

After deriving IRs from the AH analysis, Miller and Vicente (1999) then performed a Hierarchical Task Analysis (HTA: Shepherd, 1989) of the same process and developed a separate set of information requirements. HTA breaks down tasks into a part-whole hierarchy of stem and leaf plans of action. It expresses sequence constraints between the plans and denotes the role of various actors in carrying them out. Miller and Vicente (1999) concluded that, even when completed sequentially, system- and task-based analysis techniques each contributed unique and complementary requirements.

Jamieson (2002a) extended the task-based analysis to address the behavior of the automated controllers used in the process. The HTA had not included the controllers because the primary knowledge source driving the HTA was the operating procedures. The procedures assume that the behavior of the controllers is; a) known to the operator, and b) reliable. The AH had also not captured the activity of these controllers because work domain analysis examines the object of control (i.e., the system) and not the control itself (Hajdukiewicz & Vicente, in press). Thus, the role of the automation had not been translated into requirements for the novel interface that was to be designed. This presented a serious problem because automation plays an important role in the effective control of the AHR.

To fill in this gap, a Control Task Analysis (CTA) was conducted to supplement the HTA. Another task-based approach, CTA identifies the requirements associated with known classes of events. In this particular application, the events are the control actions required to direct the process in a productive way. A non-linear information processing framework called the Decision Ladder (DL; Rasmussen, 1976) was used to perform the CTA. The DL is a sequence of information processing steps and intermediate states of knowledge. The framework is non-linear because the steps do not have to be completed in a specific sequence. Rather, the framework allows an actor (a generic term that incorporates the operator or the automation) to take advantage of shortcuts in association between the steps.

RESULTS

Determination of IRs Identified by Each Analysis

A Venn diagram (Figure 1) shows the proportion of the total IRs accounted for by each analysis and the overlap between the various analyses. Take, for example, the proportions for the AH. The AH alone identified 51% of the IRs identified by all three analyses. However, the HTA identified a proportion of the same IRs, namely 23% of the total set. All three analyses (ADS, HTA, and CTA) identified the same 10% of the total IRs. However, there was no overlap between ADS and CTA that was not also shared with the HTA. Generally speaking, there was a large overlap (at least 16%) in the information requirements generated by each analysis. However, there is also substantial uniqueness (about 5% in the case of the two task analyses) in each of them. Both of these findings conform to the qualitative observations of Miller and Vicente (2001).

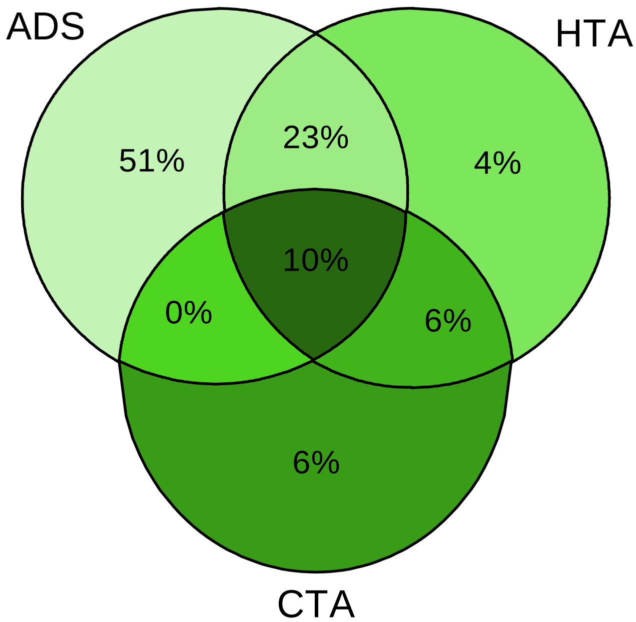

Figure 1: Proportion of all IRs captured by each analysis or combination of analyses (circles not to scale).

The very large number of IRs identified by the AH can be attributed to the scope of the analysis. System-based analysis looks at all of the physical and functional constraints that govern the system. In contrast, the two task-based analyses examine only the subset of actions that are explicitly planned for or automated. Thus, by nature, the AH adopts a broader scope and captures more IRs. Some of these requirements may appear trivial, but it is this rigorous nature that allows the AH to be an event-independent analysis.

Evaluation of IRs Met by the Existing Interface

Figure 2 compares the combined number of IRs generated from all sources (black columns) to the number of IRs met by the current interface (white columns). The first nine pairs of columns at left are taken from the AH; whereas the

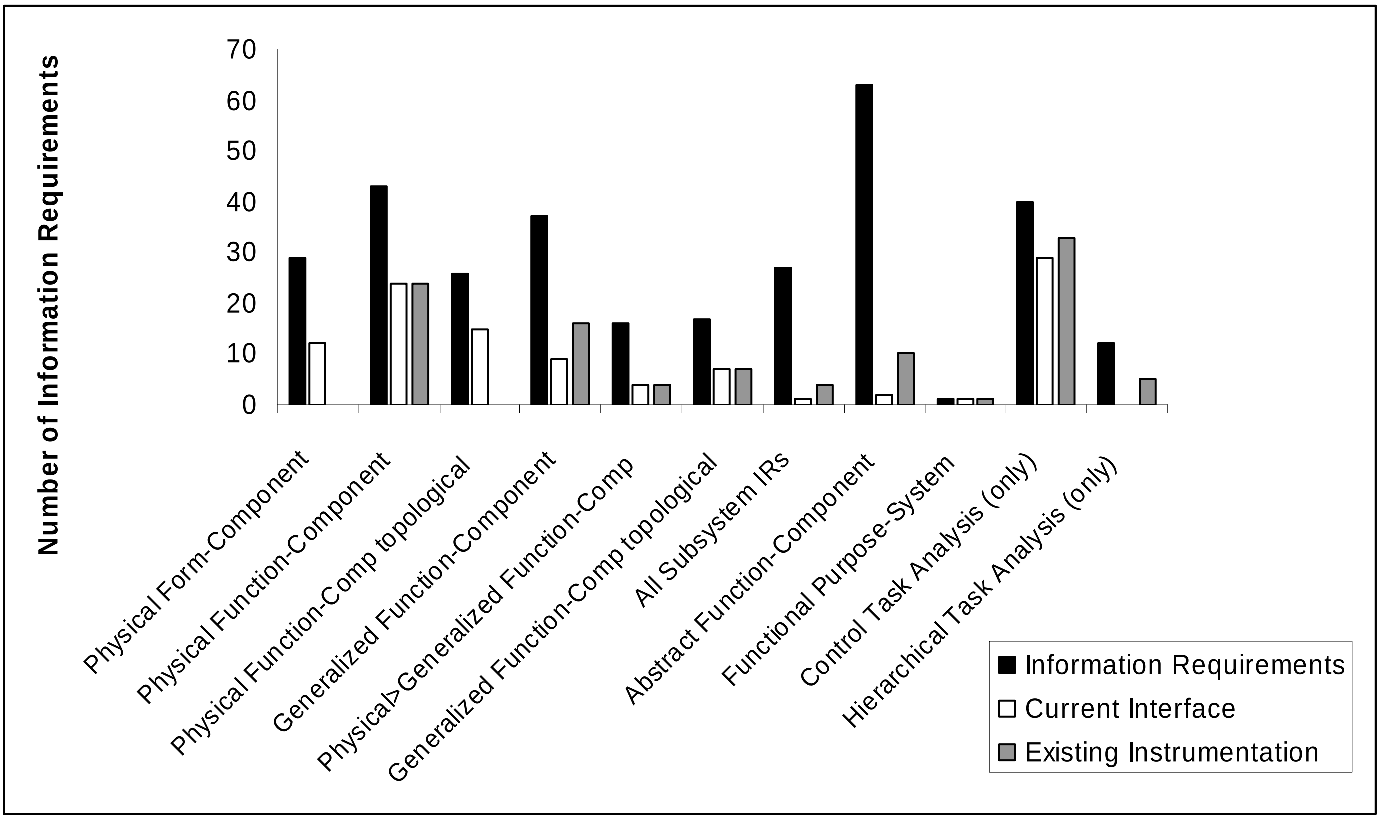

Figure 2: Comparison of IRs identified versus IRs included in the current interface.

rightmost two are from the CTA and HTA (as labeled). There is a clear shortfall in the current interface compared to the requirements identified, although the reasons for this are not consistent across the categories. At low levels of abstraction, such at the Physical Form level, the interface excludes many IRs to reduce display clutter and optimize for normal operations. Thus, rarely used valves have no icons or identifiers on the displays. At a higher level, many Physical Function and Generalized Function IRs at the component level are not measured, although they could be. This is typically a cost consideration, as maintaining field instrumentation is expensive. This shortage of information propagates upwards, limiting the availability of aggregated and abstract function information. In contrast, a majority of the CTA requirements are met in the existing interface, largely because they are required for automatic control and must therefore appear in the instrumentation system. Once a data value is created, it invariably appears in the interface. Finally, it is notable that none of the HTA-only IRs are met. There are two reasons for this. First, HTA requirements either refer to a procedure step or information needed to support a step. The former has no explicit instrumentation requirement while the latter would be captured by the other analyses as well. Second, the written procedures themselves meet these requirements. Thus, there is no perceived need to include them in the interface.

IR Coverage Possible With Existing Instrumentation

Figure 2 also assesses what proportion of the IRs *could* be met with the existing sensor set (gray columns) if the necessary derivations of higher-order properties were performed. Comparing the white and gray columns, it is clear that there is not a great deal of information that could be supported by the existing instrumentation system that is not already made available in the interface. What remains falls primarily into three categories; relationships between constraints at the Generalized Function level, aggregated information about subsystem performance, and derived mass and energy information at the Abstract Function level. Thus, the existing interface appears to be exploiting a majority of the information available through the current instrumentation. The comparison appears to suggest that, in order to provide substantially more information to the operator, the instrumentation would need to be expanded.

DISCUSSION

Limitations

There are at least two difficulties with the counts that make up the comparisons in Figures 1 and 2. First, all IRs are treated as having the same value. This can be misleading because any one IR can describe a much more critical constraint than another. This is especially true when one of the constraints in question is functional and the other is a constraint on action. Second, some task constraints suffered from a granularity problem. With the HTA, it was often possible to break each task down further and further to the point of triviality. Doing so, however, would artificially inflate the number of IRs from that analysis.

Given these problems, how are the analyses to be meaningfully interpreted? The answer is that they give qualitative insight into the value of each analysis. The large overlap confirms that system- and task-based analyses are both productive methods for building a knowledge base for interface design. However, each analysis clearly identifies requirements not cited by the others. Thus, the analyses are mutually re-enforcing.

Implications for System Design

Figure 2 shows the proportion of the total information requirements that are met by the existing information system and how many more could be supported by that system. While there is some room for expanding the information available to operators of the current process, the bulk of the shortfall in the existing interfaces cannot be made up with the existing sensor suite. These requirements come from both system- and task-based analyses, suggesting that contributions from both methods will be constrained by available sensors. Thus, improvements in the quantity of relevant information provided to operators would require substantial investments in infrastructure. Reising and Sanderson (2002) have considered some of the performance implications of limited information availability.

The results of these analyses were used to develop a novel ecological interface for a model-based simulation of the AHR process (Jamieson, 2002a). Unlike the actual system, the simulator provided nearly all of the information called for in the analyses. Professional operators using the novel interface to manage both planned for and unanticipated events enjoyed several performance advantages over those using the current interface (Jamieson, 2002b). Interestingly, however, operator comments on the effectiveness of the interface suggested that the displays based primarily on information that was absent in the current system were not the most valuable. Rather, the operators using the new interface reported gaining the most benefit from the graphical forms that integrated information that is available in the current interface. These findings call attention to the important question of whether larger gains in performance will come from increasing the operator's range of access to information, or by improving the quality of the display of that information. In short, does content trump form or vice versa?

Together, these analysis and experimental results can help interface designers and instrumentation engineers to evaluate when additional sensors and/or derivation are required to support more effective control.

ACKNOWLEDGEMENTS

Nova Chemicals, Ltd. and the Natural Sciences and Engineering Research Council of Canada provided financial support for the work described in this article.

REFERENCES

Chow, R., & Vicente, K. J. (2002). A field study of emergency ambulance dispatching: Implications for decision support. In Proceedings of the Human Factors and Ergonomics Society 46th Annual Meeting (pp. 313-317). Santa Monica, CA: HFES.

Dinadis, N. & Vicente, K. J. (1999). Designing functional visualizations for aircraft systems status displays. International Journal of Aviation Psychology, 9, 241-269.

Hajdukiewicz, J. R. & Vicente, K. J. (in press). A theoretical note on the relationship between work domain analysis and task analysis. Theoretical Issues in Ergonomics Science.

Jamieson, G. A. (2002a). Ecological interface design for petrochemical process control: Integrating Task- and System-based approaches (CEL-02-01). Cognitive Engineering Laboratory: University of Toronto.

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

Jamieson, G. A., & Vicente, K. J. (2001). Ecological interface design for petrochemical applications: supporting operator adaptation, continuous learning, and distributed, collaborative work. Computers and Chemical Engineering, 25, 1055-1074.

Miller, C. A., & Vicente, K. J. (1998). Abstraction decomposition space analysis for NOVA's E1 acetylene hydrogenation reactor (CEL-98-09). Cognitive Engineering Lab: University of Toronto.

Miller, C. A., & Vicente, K. J. (1999). Comparative Analysis of display requirements generated via task-based and work domain-based analyses in a real world domain: NOVA's acetylene hydrogenation reactor (CEL-99-04). Cognitive Engineering Lab: University of Toronto.

Miller, C. A., & Vicente, K. J. (2001). Comparison of display requirements generated via hierarchical task and abstraction-decomposition space analysis techniques. International Journal of Cognitive Ergonomics, 5, 335-356.

Rasmussen, J. (1976). Outlines of a hybrid model of the process plant operator. In T. B. Sheridan & G. Johannsen (Eds.) Monitoring behavior and supervisory control. New York: Plenum.

Rasmussen, J. (1985). The role of hierarchical knowledge representation in decision making and system management. IEEE Transactions on Systems, Man and Cybernetics, SMC-15, 234-243.

Reising, D. V. C., & Sanderson, P. M. (2002). Work domain analysis and sensors II: Pasteurizer II case study. International Journal of Human-Computer Studies. 56, 597-637.

Shepherd, A. (1989). Analysis and training in information technology tasks. In Diaper, D. (Ed.). Task analysis for human-computer interaction (pp. 15-55). Ellis Horwood, Ltd.: Chichester.

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

Vicente, K. J., & Rasmussen, J. (1992). Ecological interface design: Theoretical foundations. IEEE Transactions on Systems, Man, and Cybernetics, SMC-22, 1-18.