Cost-Justifying Investments in Advanced Human-Machine Interface Technologies I: A Cost-Benefit Framework for the Process Industries

Greg A. Jamieson
Mechanical & Industrial Engineering
University of Toronto
Toronto, ON Canada

Dal Vernon C. Reising
ACS Advanced Technology
Honeywell International, Inc.
Minneapolis, MN USA

Advanced human-machine interfaces (HMIs), such as those developed under the ecological interface design framework, continue to show substantial advantages for supporting effective operator control (Vicente, 2002). However, prospective industry users of these technologies have expressed a need to make a quantitative economic case for designing and implementing advanced HMIs. To date, no comprehensive cost justification study has been published on advanced HMIs. The purpose of this paper is to report original work on a cost-benefit framework for advanced HMI's. We first present a brief summary of findings from a literature review of existing human factors cost justification studies and present a working list of metrics. We then describe a general cost-benefit framework derived from this list of metrics and discuss issues to be considered in applying this model in practice.

INTRODUCTION

One of the challenges for industry in adopting a new technology is establishing the relative return-on-investment (ROI) of that technology compared to competing capital projects. The deployment of advanced Human-Machine Interface (HMI) design approaches in the process industries suffers from this same challenge, and perhaps is at a disadvantage to other technologies – such as advanced process control (APC) – in that convincing cost-justification data is not as readily available for HMI investments as it is for other investments.

Although there are several recent examples of process industry applications of advanced HMI design techniques (e.g., Burns, Garrison, & Dinadis, 2003; Jamieson, 2002), technology transfer to industry will be limited without a sound cost-justification for the technology. This paper presents original work on an initial cost-benefit framework for HMI evaluations for the process industries. The framework can be adapted, depending on the degree of control and fidelity available to those persons conducting the economic evaluation (see Verma, 2003 for an example).

This paper presents the method by which the cost-justification framework was constructed, including assumptions made for applying the framework, as well as an explanation of the framework itself and means by which it might be adapted to local conditions for its use. The paper concludes with a discussion of framework use and its limitations.

METHOD

Framework construction followed roughly three main steps: conducting a broad-based literature survey to find related work, identifying relevant metrics for determining the impact of HMI designs, and constructing a cost-benefit model that established the relationships between said metrics.

Literature Survey

We conducted a broad-based literature review to gather metrics to consider for inclusion in the cost-benefit framework. We reviewed three general literature areas; each of which is summarized below.

Measurement techniques in human factors. Studies were reviewed that focused on assessing human operator behavior in process control (e.g., Moffat, 1990; Sanderson, Verhage, & Fuld, 1989). These articles presented a wide variety of possible performance measures for consideration in the current model construction effort, such as trajectories through state-space vectors, accuracy of diagnostic activity, and so on.

Economic justification for software usability testing. A number studies were reviewed that reported on cost-benefit analyses of applying human factors principles to software design (e.g., Bias & Mayhew, 1994; Karat, 1997). These studies reported that human factors input in the development of computer-based tools can lead to substantial cost benefits. Our intent was to leverage this work in justifying human factors in advanced HMI design. Measures for assessing both the cost of, and return on, the usability intervention from these studies were also considered.

ROI assessments for Automation Deployment. Articles were reviewed that discussed either how to calculate ROI or the realized ROI for automation solutions for the process industries (e.g., Bullerdiek & Hobbs, 1995; Gill et al, 1993). Solutions included introducing APC applications or real-time optimization technologies. The purpose for this focus was to capture industry-relevant economic indicators for inclusion in the cost-benefits model presented here.

There were several shortcomings across these three bodies of literature. For example, most of the user tasks in the cost justification of usability studies were discrete and repetitive. These task characteristics are very different from those of a plant operator, whose primary activity when using such advanced HMIs is continuous monitoring. Further, the human performance measures obtained in many of these studies, such as errors or task completion time, were easily translated into economic data. Attaching concrete costs to operator activities in the process industries is not as straightforward. Thus, these studies were of marginal utility for the current effort.

Similarly, the main drawback of the literature on human factors in process control was that many of the measures are not easily translated into economic numbers. Metrics such as frequency of control actions and accuracy of situation awareness do not directly map onto dollar amounts. Finally, a shortcoming of the ROI for automation literature was that very few measures reported for the introduction of automation could be directly attributed to only the HMI component of that automation.

Measure Identification

Despite these limitations, the literature survey informed the development of a list of potential economic measures and helped in clarifying the terms to better fit petrochemical applications. The resultant measures can be divided into three broad categories.

1. Joint Human/Process performance: These measures reflect the performance of the process under joint human and automated control. They are primarily generated from process data.
2. Measured Operator performance: These measures reflect operator behaviors and states of knowledge that have an indirect relationship to the process performance. These measures are generally derived from an evaluation of process data crossed with operator action assessments.
3. Subjective Operator ratings: These measures address operator attitudes and opinions about the support tools, the work environment, etc. They are acquired from operator surveys or verbal protocols.

Each successive category of measures is less concrete and more difficult to translate into economic indicators. This does not mean that the less concrete measures relate to constructs that are less valuable. Rather, these values are merely harder to extract.

A subset of metrics that highlight the nature of overall resulting list of user interface measures is presented in Table 1, with metrics grouped within each of these three broad categories,. The table consists of five columns:

1. The **constructs** of interest
2. The **metrics** used to evaluate the construct
3. A **definition** of the metrics
4. A **calculation** or measurement unit
5. An indication of the **assessment** method used to acquire the measure

Table 1: An illustrative, partial list of metrics considered for inclusion in the Cost-Benefit Framework developed

Construct	Metric	Definition	Calculation	Assessment
Human/Process Performance				
Productivity	Throughput vs. design	Product rate versus designed max. rate	throughput/design*100	process data
Efficiency	Utility cost (product)	Utility cost expended to produce product	utility cost*(1-product flow/raw flow)	process data
Disturbances	Freq. of process disturbances/incidents	Rate at which process disturbances are observed	disturbances observed/unit time	process data + evaluation
Quality	Product quality	The degree to which the product has desired chemical attributes	analyzer	process data
Cost of abnormal events	Cost of lost production	The economic value of product not produced as a result of an abnormal event	value of product*product not produced	process data + evaluation
Measured Operator Performance				
Cost	Training cost	Cost of training operators to use new interface	training time * mean hourly wage	empirical
Control performance	Trajectory evaluation (deviation)	Performance in maintaining a process variable value relative to an idealized operating curve	1-(process var. deviation area/tot. dev. area)	process data + calculation
Control performance	Control action errors	Any control action that will not improve situation	count	assessment
Operator performance	Process anomaly detection time	Time elapsed between onset of anomaly and operator indication of awareness	time	observation
Operator performance	Diagnosis accuracy	Scored accuracy of final operator diagnosis of cause of anomaly	evaluate	observation + evaluation
Subjective Operator Ratings				
Operator performance	Accuracy of process state descriptions	Accuracy with which an operator can describe the process state	score	evaluation
Operator performance	Remote event awareness	Recognition of occurrence of events outside of assigned area	Situation Awareness measures	evaluation
Operator performance	Existing skill utilization	Degree to which operator skills are utilized in job performance	survey	survey
Operator performance	Operator self-confidence	Operator's sense of self-confidence in executing control	scaling	scale
Operator performance	Level of comfort/stress	Reported stress level	scaling	scale

Framework Construction

We adopted a linear programming approach to creating a cost-benefit-justification framework for advanced UI design techniques. The mixed-integer model consisted of an "objective function" that was subject to the performance of the various equations which captured the relationships between various measures identified in Table 1. The equations and measures were approximately grouped by the three functional categories described above; joint human/system performance, measured operator performance, and subjective operator ratings.

In developing the framework, it became apparent that assumptions had to be made about what data was available for a particular process. For example, assessing the impact of an interface on production value necessitates having established targets and monetary values for each of the process streams. In an effort to retain some of the depth of our most general case we elected to develop a *comprehensive* framework that assumes the availability of a great deal of background data to perform the cost/benefit calculation. However, the specific terms used in a given instance of the applied framework depends on the information available (cf., Verma, 2003).

RESULTS

The cost-benefit framework is presented in complete form in Equation 1. The main equation (1.0) expresses the overall cost or benefit of the HMI as a function of the following terms: production value, utility costs, quality losses, event costs, expected incident costs, and the fielding cost.

First, fielding costs (Eq. 1.4) are factored into the framework as fixed costs for operator training, display development, and implementation. These factors are scaled according to the display lifecycle relative to the observation time.

Joint Human/Process Performance Equations

The production value (Eq. 1.1) is expressed as the sum of the accumulated monetary values of process flows. The utility cost (Eq. 1.2) is expressed as the sum of the product of the flow rate of utility variables and their associated monetary costs. Quality losses (Eq. 1.3) are expressed as the product of the flow rate of process variables and a quality penalty for each.

The event cost term (Eq. 1.5) accounts for the costs associated with abnormal events that were common to the two HMI designs during some defined observation period (e.g., in a control comparison using a simulator, for example, or some set amount of weeks or months in a "before-and-after" assessment; see "Framework Use" discussion below). The first seven factors in this term are fixed costs that must be determined for each event. The last factor, a product of the available flare flows and the value of the flared stream, accounts for flare losses.

Operator Performance Equations

The expected incident cost (Eq. 1.6) combines a series of operator performance and subjective rating factors to anticipate likely future incident costs, thereby "normalizing" for all events, not just those accounted for in Eq. 1.5. The term assumes the availability of an event frequency projection, an anticipated average cost of those events, and the lifecycle of the display.

Measured operator performance. The risk mitigation factor (Eq. 1.6.1) accumulates the weighted sum of four components associated with risk-averse behaviors and qualities. The coefficients here allow for flexibility in establishing the relative importance of each component and term in the framework. Fault management performance (Eq. 1.6.1.1) is defined as a weighted sum of the ratios of detection time, correction time and recovery time over the off target time. The situation awareness component (Eq. 1.6.1.2) consists of weighted scores of state description, event awareness, and diagnosis accuracy assessments.

Subjective operator ratings. Skill utilization (Eq. 1.6.1.3) attempts to capture the combined proportions of operator skill that are exercised by the interface. These include the existing skill set, a new skill set (e.g., new training), judgment utilization, and education utilization. The assuredness component (Eq. 1.6.1.4) combines the weighted operator self-ratings of stress and self-confidence.

DISCUSSION OF USE AND LIMITATIONS

Framework Use

We constructed the cost-benefit framework based on the findings from our review. This framework provides an initial structure for assessing the costs and benefits for HMIs in process systems. In its present state, the framework can be most effectively applied to comparisons between contemporary interfaces and the advanced HMIs. The comparison could be accomplished in one of two ways. First, the metrics could inform a 'side-by-side' comparison of the contemporary interface and the new HMI in a simulator. This approach is preferred because event scenarios can be selected to explore issues of interest in both interface suites. Second, the metrics could be used in a 'before-and-after' comparison using historical data from the same unit on which the advanced HMI was deployed. In this scenario the cost-benefit comparison would only become available after the HMI had already been implemented and the analyst would surrender control over the event cases.

Although not ideal, this latter approach is how many of the ROI studies for process automation have been conducted. With either approach, the gaps noted below are constant between interface conditions, allowing the analyst to develop an index value as opposed to an actual cost/benefit ratio.

Regardless of whether the framework is used in side-by-side or before-and-after comparisons of HMI designs, several comments can be made about its application. First, with respect to Eq. 1.1, an assumption of the Comprehensive

Figure 1: The Comprehensive Cost-Benefit Framework

(1.0) $Cost/benefit = ProdVal - UtilityCost - QualityLoss - FieldingCost - EventCost - ExpectedIncidentCost$

(1.1) $ProdVal = \sum_{i=1}^{n}\left[\int_0^T (TargetFlow_i - FlowDev_i)dt\right] \times FlowValue_i$ for n process (i.e., non-utility) flows (i); T=observation time

(1.1.1) $FlowDev_i = \begin{bmatrix} \lambda_1|Flow_i - TargetFlow_i| - \lambda_2(Flow_i - RangeFlow_{UL}) - \lambda_3(RangeFlow_{LL} - Flow_i) \\ -\left[\lambda_4(|TrajFlow_i - Flow_i| - TrajDeadBand_i)\right] \end{bmatrix}$,

where: $\lambda_1, \lambda_2, \lambda_3, \lambda_4 \in [0,1]$, (i.e., the conditions are binary)

$\lambda_1 + \lambda_2 + \lambda_3 + \lambda_4 \le 1$, (i.e., zero or one condition can be active at any time)

(1.2) $UtilityCost = \sum_{u=1}^{k}\int_0^T (UtilityRate_u \times UtilityCost_u)dt$ for k utilities(u) such as electricity, steam, furnace fuel, cooling water, etc.

(1.3) $QualityLoss = \sum_{i=1}^{n}\int_0^T (Flow_i \times QualityPenalty_i)dt$ for n process variables

(1.4) $FieldingCost = \dfrac{(TrainingCost + DisplayDevelopmentCost + ImplementationCost)}{(DisplayLifeCycle/T)}$

(1.5) $EventCost = EquipmentRepair/Replacement + SpillCleanUp + WasteDisposal + InvestigationLabor + RepairLabor + OffSpecBlending + LegalCosts/Fine + \sum_{a=1}^{m}(FlareFlow_a \times StreamValue_a)$

for m flare flows (a)

(1.6) $ExpectedIncidentCost = \dfrac{(1 - RiskMitigationFactor)(EventFreq \times AvgEventCost)}{(DisplayLifeCycle/T)}$

(1.6.1) $RiskMitigationFactor = [\phi_1 FaultMgmtPerf + \phi_2 SitAwareness + \phi_3 SkillUtil + \phi_4 Assuredness]/4$,

where: $\phi_1 + \phi_2 + \phi_3 + \phi_4 = 4$, and $0 \le \phi_1, \phi_2, \phi_3, \phi_4 \le 4$

(1.6.1.1) $FaultMgmtPerf = \left[\gamma_1\left(\dfrac{DetectionTime}{OffTargetTime}\right) + \gamma_2\left(\dfrac{CorrectionTime}{OffTargetTime}\right) + \gamma_3\left(\dfrac{RecoveryTime}{OffTargetTime}\right)\right]/3$

where: $\gamma_1 + \gamma_2 + \gamma_3 = 3$, and $0 \le \gamma_1, \gamma_2, \gamma_3 \le 3$

and: (1.6.1.1.1) $OffTargetTime(i) = (\alpha_i \times AnomalyDetTime(i) + FirstContrCorrTime(i) + RecoveryTime(i))$,

where: $\alpha_i \in [0,1]$ is the anomaly/anticipated unusual distinction

(1.6.1.2) $SitAwareness = \left[\sigma_1\left(\dfrac{StateDescScore}{100}\right) + \sigma_2\left(\dfrac{EventAwarenessScore}{100}\right) + \sigma_3\left(\dfrac{DiagnosisAcc}{3}\right)\right]\Big/3$,

where: $\sigma_1 + \sigma_2 + \sigma_3 = 3$, and $0 \le \sigma_1, \sigma_2, \sigma_3 \le 3$

and: StateDescScore = (0-100), EventAwarenessScore = (0-100), and $DiagnosisAccuracy \in [0,1,2,3]$

(1.6.1.3) $SkillUtil = \left[\alpha_1\left(\dfrac{ExistingSkillUtil}{100}\right) + \alpha_2\left(\dfrac{NewSkillUtil}{100}\right) + \alpha_3\left(\dfrac{JudgmentUtil}{100}\right) + \alpha_4\left(\dfrac{EducationUtil}{100}\right)\right]\Big/4$,

where: $\alpha_1 + \alpha_2 + \alpha_3 + \alpha_4 = 4$, and $0 \le \alpha_1, \alpha_2, \alpha_3, \alpha_4 \le 4$

and: *Util = (0-100)

(1.6.1.4) $Assuredness = \left[\beta_1\left(\dfrac{SelfConfidence}{100}\right) + \beta_2\left(\dfrac{(100 - StressScore)}{100}\right)\right]\Big/2$

where: $\beta_1 + \beta_2 = 2$, and $0 \le \beta_1, \beta_2 \le 2$

and: SelfConfidence = (0-100) and StressScore = (100-0)

Assumptions: All flows can be assigned a value and a target (i.e., target, range, or trajectory)
Event history is known
Event Frequency & average Event Cost are known

framework is that all process flows have associated targets to be achieved. In the applied case, this assumption may not hold. If the assumption does not hold, then Eq. 1.1 could be instantiated as some subset of all process flows for which targets were known or as *ProdVal* = ∑ ∫ *(Value x Flow)dt* for all product flows only (i.e., product flows = process flows – utility flows).

Second, with respect to Eq 1.6, in which a projection of future event frequency must be made, the user of the framework might assume the same event rate as that seen in historical incident reporting. This assumption is a more conservative approach than speculating about a new base rate for event frequencies. Typically, HMI designers might expect that the advanced HMI should lead to fewer events, but building cost-benefit analyses around events for which the frequency has changed to some undetermined base rate as a result of the design change has proven challenging, as a whole, to various Abnormal Situation Management Consortium solution efforts, such as state estimation and early event detection (Mylaraswamy & Bullemer, 2000). Similarly, the conservative approach might be relaxed with confidence ranges or best-case vs. worst-case estimates, for example.

Finally, with respect to Eq. 1.6.1.1-1.6.1.4, in our professional experiences working with process industry representatives, it has proven difficult to assign an economic value to these measured operator performance components and subjective operator ratings. The framework accounts for this difficulty by multiplying the expected cost of forecasted events (assumed to be constant for both HMI designs) by the fraction created by subtracting these summed scores from 1. So, as diagnostic accuracy, skill utilization, and so on improve, it is assumed the process is at less risk (i.e., the risk mitigation factor approaches 1 and the likelihood of an event approaches 0). This line of reasoning can be applied for both the side-by-side and before-and-after uses of the framework.

Limitations

Clearly, several key gaps remain to be addressed before this framework can be applied by practitioners. First, the framework could be enriched to assign quantitative costs and benefits to the measured operator performance parameters and the subjective operator ratings. This would allow these parameters to be more meaningfully compared to the joint human/system process performance parameters. Second, the framework could be compared to methods for assessing the financial viability of other information technologies.

It is important to note that local applications of the Comprehensive framework will require tweaking to the specific application. For each specific case, the practitioner must assess the availability of process data to populate the framework. Without sufficient data, the framework could provide misleading information. The user must also determine coefficients for the framework parameters (e.g., the γ, λ, β, and so on in Equation 1). This requires making difficult decisions about which factors are more important than others.

CONCLUSIONS

Our review of measures for the assessment of human operator performance and the determination of economic impacts of that performance yielded two valuable lessons. First, the existing literature on cost-justifying usability does not transfer well to HMIs for complex systems, primarily because the user tasks are very different. Second, the performance measures used in evaluating HMIs for process control are not easily translated into economic values.

We believe the work reported here is an initial step towards filling these gaps in the current literature. Verma (2003) presents an implementation of the Pragmatic framework, as applied to an HMI evaluation study. The model was used to evaluate data obtained from an empirical study that compared contemporary and advanced HMI technologies (Jamieson, 2002). The aim of that paper is to identify more of the gaps in our knowledge of how to make a complete quantitative assessment of the economics of advanced HMI design. However, the human factors community as a whole needs to make stronger efforts to document ROI impacts for human factors solutions, if this professional community is to have a substantial impact on the industrial profitability, worker health, and public safety.

ACKNOWLEDGEMENTS

This work was supported by cash and in-kind contributions from Nova Chemicals, Ltd., The Natural Science and Engineering Research Council, and Honeywell, Inc. The authors thank company representatives from the Abnormal Situation Management Consortium for their comments on an initial list of metrics.

REFERENCES

Bias, R. & Mayhew, D. (1994). *Cost-justifying usability*. New York: Academic Press.

Bullerdiek, E. A., & Hobbs, J. W. (1995). Advanced controls pay out in 6 weeks at Texas refinery. *Oil & Gas Journal*, *93*(*25*), 48-52.

Burns, C. M., Garrison, L., & Dinadis, N. (2003). From analysis to design: WDA for the petrochemical industry. In *Proceedings of the Human Factors and Ergonomics Society 47th Annual Meeting* (pp. 258-262). Santa Monica, CA: HFES.

Gill, M. R., Sisk, L. B., Warren, W. F., & Simpson, T. W. (1993). PLC/PC monitoring control systems a boon for smaller NGL plants. *Oil & Gas Journal*, *91*(*44*), 62-63.

Jamieson, G. A. (2002). 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.

Karat, C. M. (1997). Cost-justifying usability engineering in the software life cycle. In Helander, M., Landauer, T. K., & Prabhu, P. (Eds.). *Handbook of human-computer interaction* (2nd ed.). Amsterdam: Elsevier.

Moffat, B. (1990). Normalized performance ratio – a measure of the degree to which a man-machine interface accomplishes its main operational objectives. *International Journal of Man-Machine Studies*, *32*(*1*), 21-108.

Mylaraswamy, D., & Bullemer, P. (2000). Fielding a multiple state estimator platform. Paper presented at the NPRA Computer Conference, Chicago, IL. November 13-15.

Sanderson, P. M., Verhage, A. G., & Fuld, R. B. (1989). State-space and verbal protocol methods for studying the human operator in process control. *Ergonomics*, *32*(*11*), 1343-1372.

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

Verma, V. (2003). *Developing A Cost Benefit Model for An Ecological Interface.* Unpublished M.A.Sc. Thesis. University of Toronto.