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ESTABLISHING HUMAN PERFORMANCE IMPROVEMENTS AND ECONOMIC BENEFIT FOR A HUMAN-CENTERED OPERATOR INTERFACE: AN INDUSTRIAL EVALUATION

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A controlled comparison of a human-centered operator interface to that of a traditional distributed control system interface was conducted to establish the human performance improvement. Twenty-one professional petrochemical plant operators completed a series of matching process upset scenarios on their respective plants' high-fidelity training simulators. Each scenario contained an equipment or process failure previously experienced in the real plants. The results indicated that operators using the human-centered design completed scenarios an average of 7.5 minutes faster (41% improvement over the traditional interface), successfully dealt with failures in 96% of the cases (a 26% improvement), and recognized the presence of the failure before the first process alarm in 48% of the cases (a 38% improvement). These performance results were then used as input to a Monte Carlo simulation that estimated the economic benefit for the human-centered interface at $1,090,000 CAD per year for a plant of comparable size.

INTRODUCTION

The purpose of this project was to determine both the human performance improvement of a Human-centered Interface recently implemented for a petrochemical plant as well as the return-on-investment that this improvement yielded. Establishing the business justification, or return-on-investment of human factors in general, and human-machine interfaces in complex systems in particular, has not been easily established in the past (see Rouse and Boff (1997) and Jamieson and Reising (2004) for discussions on the difficulty for these respective areas).

The Abnormal Situation Management (ASM) Consortium pioneered a new approach to operator interface design for the process industries during development of their Abnormal Event and Guidance Information System (AEGIS) prototype in 1996 (Bullemer, 1998; Bullemer et al, 1999). This human-centered interface was designed via scenario-based task analyses (cf., Carroll, 1995) and was intended to improve the console operator's situational awareness to changing plant conditions so that abnormal events could be prevented outright or mitigated more effectively were they to occur. NOVA Chemicals applied and further extended this approach when it built new ethylene and polyethylene plants at their Joffre manufacturing site in 2000 (Errington, DeMaere, & Wade, 2005). The extensions included the integration of trend information and access to additional online information.

Features of the Human-Centered Interface

NOVA Chemicals' human-centered interface was developed on a Honeywell Total Plant System (TPS) control system and the overall operator console interface layout was designed to use eight 21" screens. The upper four screens display an overview of the plant, the alarm summary page, and trends of key process variables. The console operator's working screens are two matching pair of screens (both pairs look like Figure 1(A)). Each pair of lower screens is a yoked set and integrates four levels of increasing equipment detail, along with two fixed trends.

The Human-centered Interface design was intended to provide a continuous broad overview of process conditions while simultaneously giving access to the needed detail information. The desired result was to reduce the potential for "tunnel visioning" (Moray & Rotenberg, 1989) when operators are engaged in solving complex process problems. Some of the key human-centered features include:

- Multi-windowing with controlled window management to minimize display overlays,
- Multi-level, simultaneous views of increasing plant detail
- Tabbed navigation within a display level,
- Yoked navigation between display levels (i.e., automated display invocation through pre-configured display associations for assisted, task-relevant navigation),
- Integrated trending of historical information,
- Integrated alarm management into graphics and navigation tabs,
- Right-mouse click access to online documentation, and
- Human-centered graphics design (e.g., principled, judicious color-coding; limited 3-D objects; simple, effective symbology).

In comparison, an older ethylene plant at Joffre, which has been in operation since 1984, has a more traditional industry-style operator interface (see Figure 1(B). The traditional control system's operator interface was developed prior to multi-windowing environments and typically uses a single-window-per-screen approach, where an operator might have 4 to 8 screens on the console and the process graphics

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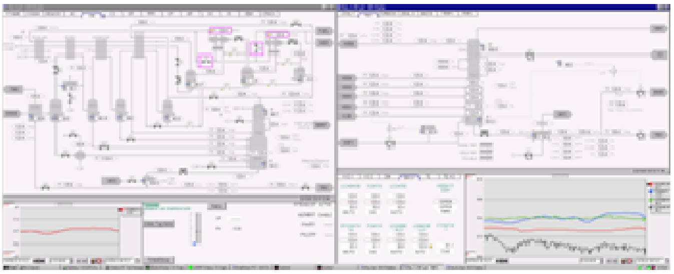
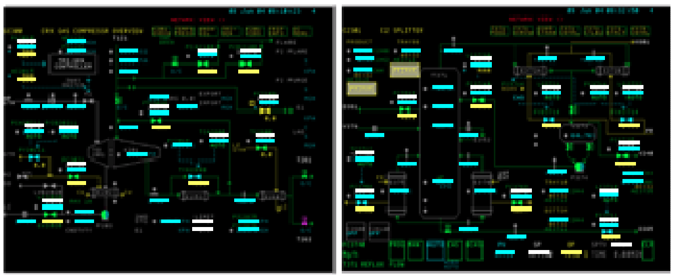


(A) The Human-centered Interface



(B) The Traditional Interface

Figure 1: Examples of the Human-centered (A) and Traditional (B) Interfaces evaluated in this study

closely emulate Piping and Instrumentation Diagram (P&ID) information presentation (c.f., Moore & Corbridge, 1996). Navigation and operator input is supported through a dedicated, specialized keyboard. Touch-sensitive screens with embedded targets in the graphics are used to supplement the keyboard for operator inputs. The older graphics system has a limited color palette with which to draw and a fixed-color, black background. A variety of colors are used to depict different operating conditions, often requiring decoding by the operator to interpret the conditions.

The traditional interface is also on a Honeywell TPS but primarily uses the previous-generation DCS workstations. The workstations are arranged into the operator console as a working group and operators have approximately eight 21" screens, along with dedicated panels for hardwired alarms and equipment controls. The upper screens are used for an overview display, trend information, and an additional alarm summary display. The bottom screens are the operators working screens, on which they can call up their process graphics.

METHOD

Participants

NOVA Chemicals' simulator training coordinators for Plants A and B selected the study participants from the pool of professional console operators at the manufacturing site. Participants were either fully qualified or in the process of qualifying for the console positions that were used in the evaluation. Participants volunteered and were informed that the objective of the study was to compare the differences in the two interfaces and not in their own performance. The participants were also informed that their results would be kept anonymous. In total, 21 operators participated: eleven console operators from Plant A, using the Human-centered Interface, and ten console operators from Plant B, using the Traditional Interface.

Experimental Environment

NOVA Chemicals has carefully developed high fidelity dynamic simulators of large portions of their plants to support their console operators' training program. The simulators are used extensively for activities such as operator training, qualification, re-certification, advanced control application and procedure development, as well as operator interface development. Plants A and B each have their own simulators and each has an operator interface that closely matches that of their respective online plants' DCS. The study was conducted using these simulators.

Experimental Design

The main objective of this study was to determine whether the Human-centered Interface better supported abnormal situation detection, diagnosis and response than did the Traditional Interface. To test this hypothesis, a between-subjects experimental design (Human-centered vs. Traditional) was used consisting of a pre-test experience evaluation and a scenario performance evaluation.

In the pre-test phase, the goal was to establish whether there were individual differences between the two operator groups with regard to their familiarity and experience with their respective interfaces that might lead to performance differences in the scenario evaluation phase. Both operator groups completed a questionnaire that captured their work experience and console qualifications. They were also asked to perform a "console round" trials by examining specific parts of the plant via their respective console interfaces, record requested readings, and generally look for any apparent off-normal conditions which had been set in each simulator.

In the scenario evaluation phase, the two groups of operators were given a set of predefined operating scenarios. Each participant was asked to monitor the simulated plant, which was initially set to a normal operating mode, and respond to an abnormal condition in each scenario when it arose. During the scenarios, display call-ups, control actions, requests for additional historical or trend information, and requests to the field operator were recorded, as well as the associated time measures. Each scenario included a plant malfunction that required the console operator to detect, evaluate and respond in order to maintain the condition of the plant.

To ensure completion of the testing period, each operator was given a maximum of 20 minutes to complete each scenario. In those cases where an operator did not resolve the scenario problem within the allotted time, they were assigned a final time value of 30 minutes, per agreement by the Project Team.

Simulator Scenario Development

The Project Team created eight simulator scenarios for the evaluation. The scenarios were designed to minimize the impact due to differences in the physical design of Plants A and B (i.e., minimize the possibility for performance differences that were due to field equipment differences and not differences between the two interfaces). The scenarios matched previously experienced upsets in Plants A and B, and ranged from fast developing faults such as pump failures to slow developing events such as a leaking pressure safety valve. The scenarios selected for the case study were:

1. Propylene compressor false load valve passing
2. Cracked gas steam turbine vacuum problem
3. Depropanizer (Plant A) / Deethanizer (Plant B) pump failure
4. Cracked gas compressor suction pressure transmitter drift
5. Temperature control valve failed closed
6. Ethylene compressor level valve failed closed
7. Cracked gas compressor discharge pressure safety valve (PSV) passing to flare
8. Turbo expander bypass valve drift open

As part of the experimental design development, the project team listed and prioritized the relative importance of the human-centered design features. These features were then mapped to the scenarios to ensure that the features which were believed to be most critical for improved human performance would be exercised in the scenarios.

Operators were asked to monitor their plants and were unaware of when an upset might occur or what the upset might be for the eight scenarios.

RESULTS

Pre-test for Individual Differences

A graphical presentation of the descriptive pre-test results is presented in the clustered box plot (Lane, 2004) of Figure 2. The only factor in which the two groups of operators differed significantly was the "Number of areas qualified in" (mean number of 6.2 versus 4.6 for Traditional and Human-centered respectively, with a mean difference of 1.6 areas), $t(19) = 2.9$, $p < .20$.

The difference in the number of areas qualified may reflect the fact that the plant with the Human-centered interface has only been in operation for 4 years, compared to the 20 years of operation for the plant with the Traditional interface.

The general conclusion concerning the pre-screening data is that the two groups of operators are comparable. In fact, if there were an experiential advantage, it would lie with the Traditional interface condition, a potentially conservative bias against the hypotheses being tested.

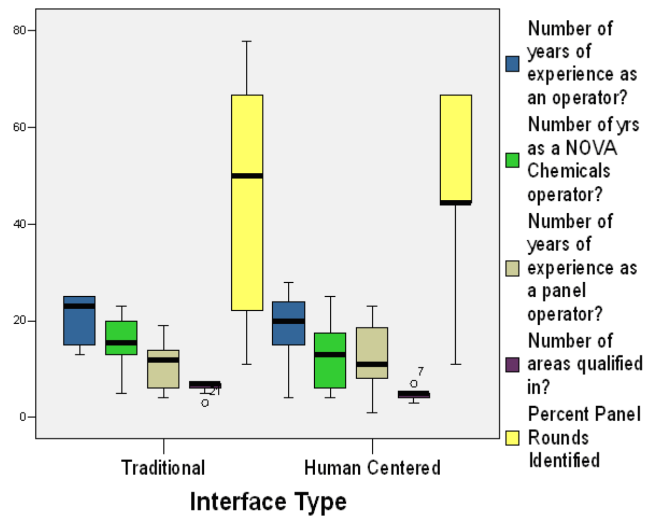


Figure 2: Clustered Box Plot summary of Pre-test differences for operator groups

Scenario Performance

After completion of the simulator trials, the scenarios were analyzed. Three of the scenarios (3, 5, and 6) turned out to be immediate malfunctions with no pre-failure warning and were easily localized by process alarms. The nature of these malfunctions, coupled with this alarm behavior, meant that the console operators had to make little or no analysis using the operator interface to determine the location and nature of the fault. As no potential response differences could be determined, these scenarios were excluded from further analyses.

A fourth scenario, scenario 1, was also removed from the analysis due a second, incidental fault in the scenario experienced by the console operators using the Human-centered interface. This second unintended fault was due the creation of a mismatch between the dynamic simulator for Plant A and the real plant that unintentionally provided misleading information to the Plant A operators. The subsequent repeated-measures ANOVAs were conducted on the remaining five Scenarios: 2, 4, 7, and 8.

Completion Time Completion Time was measured as the time at which the trainer determined that the operator had correctly identified the root cause problem and initiated the appropriate corrective actions. The time at which the failure occurred and the fault development time were kept consistent between the Human-centered and Traditional Interface conditions for each scenario.

Completion Time was analyzed in a Repeated Measures Analysis of Variance (ANOVA) with Interface Type (Human-centered vs. Traditional) as the between-subjects factor, and Scenario as the within-subjects (repeated) measure. The results indicated a significant main effect for Interface Type, $F(1,19) = 11.689$, $p < .001$. Operators using the Human-centered interface completed trials 7.5 minutes faster, on average, than did the operators using the Traditional interface. There was no significant effect of Scenario or Scenario by Interface Type interaction.

In general, operators using the Human-centered interface spent significantly less time solving each scenario than did operators using the Traditional interface (see Figure 3). The clustered box plot in Figure 3 highlights three outliers in the Human-centered condition (participants *7 and *9). However, because more participants did not solve each of the scenarios in the Traditional interface condition, they are not presented as outliers in the plot, and hence the boxes for the Traditional group extend to the top of the plot range.

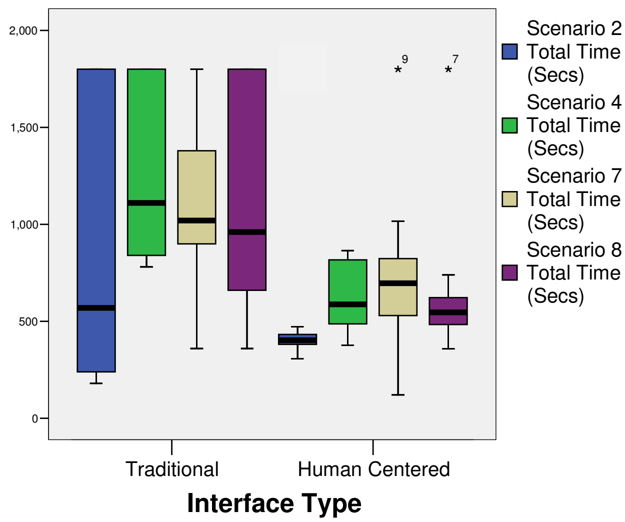


Figure 3: Clustered Box Plot summary of scenario completion time (in seconds) by Interface condition

In addition, Figure 3 also shows that the variability for the operators using the Human-centered interface was much less than that of the operators using the Traditional interface. A difference between scenarios was expected, as no attempts were made to ensure overall equality between scenarios, and the fact that the interaction between Scenario and Interface Type was not significant indicates that any differences in Scenario had no effect on the time performance of either operator group.

Early Event Detection Table 1 contains the early event detection results as a percentage of participants who identified a problem prior to the alarm indication. The data was analyzed using a Mann-Whitney Test and results indicate that operators using the Human-centered Interface detected early indications of process upsets significantly more often than the operators using the Traditional Interface, $U = 6.00$, $p < .001$.

Scenario	Interface Type	
	Traditional	Human-centered
2	0%	27%
4	10%	82%
7	10%	82%
8	20%	0%
Mean	**10.0%**	**47.7%**

Table 1: Percentage of participants indicating early event detection

Successful Completion Table 2 contains the trial completion results as a percentage of participants who successfully solved the process problem. The data were analyzed using a Mann-Whitney Test and results indicate that operators using the Human-centered Interface successfully completed significantly more scenarios than the operators using the Traditional Interface, $U = 28.00$, $p < .05$.

Scenario	Interface Type	
	Traditional	Human-centered
2	60%	100%
4	70%	100%
7	80%	91%
8	70%	91%
Mean	**70.0%**	**95.5%**

Table 2: Percentage of participants completing each scenario

Monte Carlo Analysis for Economic Benefit

The economic impact of the human performance improvements from the Human-centered interface was estimated using a Monte-Carlo simulation. The observed performance distribution of the Human-centered interface condition for both scenario completion time and the scenario completion rate were inputs to the simulation. Confidential information supplied by NOVA Chemicals from its incident reporting system for Plant B established the expected frequency ranges of incidents per year and incident costs.

Applying the completion time performance profile against the historical process-related incidents recorded in Plant B provided an estimate for one benefit of the Human-centered interface. A second benefit was calculated as a reduction in the incidents that escalate into major plant problems by assuming that the observed performance profile in completion rate would reduce the number of these incidents. Total economic benefit for the Human-centered interface was generated from the sum of these two forecasts.

Each input assumption was estimated with a 10%, 50%, and 90% value in a triangular-shaped distribution. For the observed performance distribution of completion time, estimates of 35, 41 and 48% improvements were used for the triangular distribution, respectively. For the completion rate benefit, the input range used was 21, 25, and 40%, respectively. The project team members that were knowledgeable in the operation of Plant B estimated other incident inputs to the economic model in a similar format.

Using this approach, the economic benefits from the improved operator performance using the Human-centered interface for Plant B, a 1.8 billion lb/yr ethylene plant, was estimated to have an average value of \$1,090,000 CAD/year and a most likely (median) value of \$1,000,000 CAD/year (see Table 3). No implementation costs for a Human-centered interface in Plant B were subtracted because it was anticipated that this implementation would occur as part of a larger automation upgrade project.

Statistics	Forecast Values
Trials	30,000
Mean ($K CAD)	1,089.82
Std. Dev. ($K CAD)	533.50
Median, 50% ($K CAD)	1,000.08
10 percentile ($K CAD)	482.10
90 percentile ($K CAD)	1,825.49

Table 3: Monte Carlo simulation results

DISCUSSION

This study, using professional operators to monitor plants with which they are intimately familiar and having them respond to actual failures for their plants, demonstrated that a the Human-centered interface lead to significantly better operator performance than that of the Traditional interface. Improvement was measured by early detection of the upset (an average of 38% faster), completion time (an average of 41% faster), completion success (an average of 25% more successful completions). While these results are impressive, even more meaningful was that this study successfully translated those improvements into an economic benefit as well. The Monte Carlo simulation approach estimated that these human performance improvements could save Plant B approximately $1,089,800 CAD per year.

While every attempt was made to evaluate the two interfaces on a level playing field, there were some limitations to this study, as discussed below. However, in general these limitations led to a more conservative test of the hypothesis that the Human-centered Interface would lead to better performance.

Limitations

Both operator groups were equally primed to expect upsets during the simulator scenarios and were proactively monitoring their plant's status more than might be expected under normal conditions in the real plant. It is difficult to assess the extent to which this heightened proactive monitoring creates a difference between the evaluation and real-life monitoring results -- though the Project Team believed this priming improved both groups' overall speed of response equally.

The physical differences between Plant A console and the Plant A simulator console are greater than those found between Plant B console and its simulator. Because of these differences, the Plant A operators were more restricted from performing as they might normally than were the Plant B operators. This bias is acceptable, given the hypothesis being tested, leading to a more conservative test of the hypothesis (that the Human-centered Interface better supported performance than the Traditional Interface).

Similarly, the Plant B interface, though classified as a "traditional" design, is of a higher human-centered design quality than other traditional interfaces indicative of the industry norm, making this yet again a conservative test of the hypotheses stated.

CONCLUSIONS

Human performance improvements can be translated into economic benefits. While this study provides one datum point for the economic impact good human factors can have on system design, it is clearly not comprehensive. Human factors professionals, where possible, should strive to document the economic impact that their design solutions generate (Jamieson & Reising, 2004).

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