Human Performance Models for Response to Alarm Notifications in the Process Industries: An Industrial Case Study

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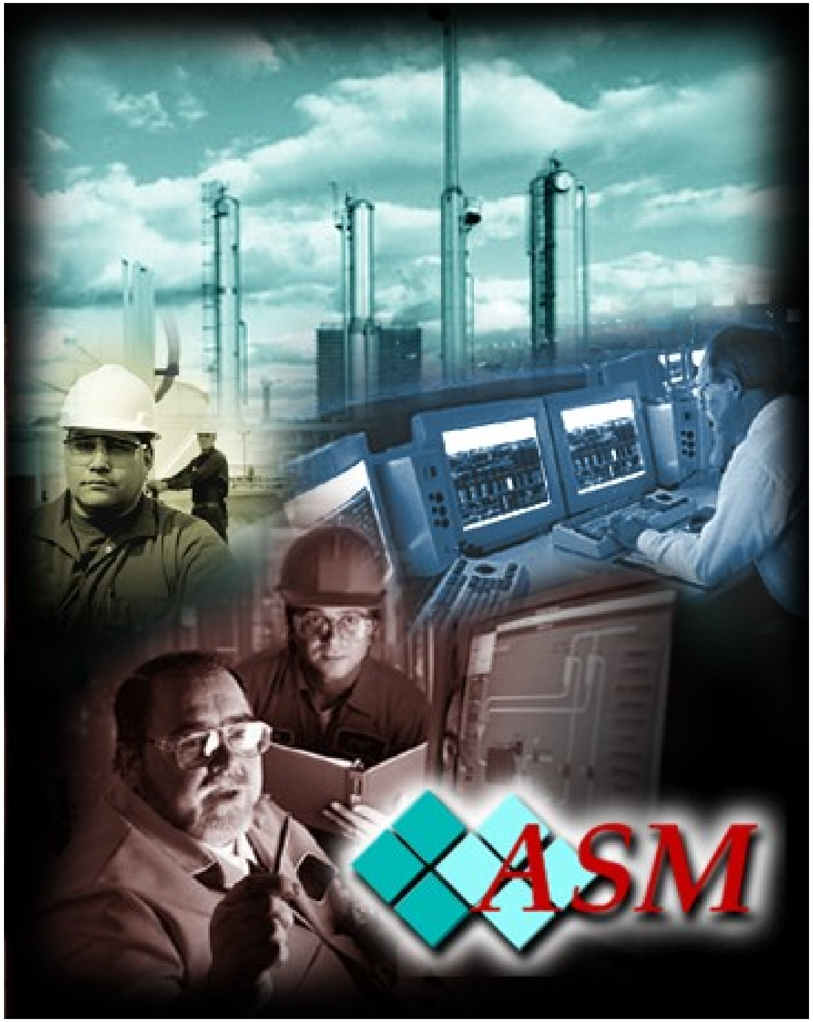

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Driving Motivation Behind the Research

- "Alarm Floods" have been an issue for the hydrocarbon processing industry since the introduction of the distributed control system in the late '70s and early '80s
  - In many cases, the alarm system and its "flooding" performance has actually contributed to or lead to a severe accident (e.g., Texaco Pembroke Refinery explosion & fire)
- The ASM Consortium has been working on alarm management solutions since the early '90s, such as
  - Alarm rationalization (Mostia, 2003)
  - User-initiated notifications (Guerlain & Bullemer, 1996)
  - Alarm setting reinforcements
  - Tracking & address "worst actors"
  - Best Practice guidelines

Alarm flooding and Operator overload is still an Issue

Driving Motivation Behind the Research

- The Engineering Equipment and Materials Users Association (EEMUA) has published a de facto industry "guideline" on alarm system performance

- Two of recommendations of this guideline relates to acceptable alarm rates
  - For normal operations, less than 1 alarm per 10 minute period
  - Following upset conditions, less than 10 alarms per 10 minute period

- These numeric recommendations were not based on fundamental human performance theory
  - Rather, they were based on the "professional experience" of those researchers that surveyed the process industries on alarm system performance (see Bransby & Jenkinson, 1998)

Driving Motivation Behind the Research

- **Previous research in the literature tends to focus on**
  - **The design and implementation of visual or auditory alarms** (O'Hara et al, 1994; Stanton, 1994; Special Issue of Ergonomics, 1995)
  - **The rate at which text alarm message can be read** (e.g., Hollywell & Marshall, 1994)

- So the question remains… **What is the maximum alarm rate at which refining and petrochemical plant operators may still reliably *respond* to those alarms?**
  - **The underlying question from the operating companies in the ASM Consortium was:**

    "Are the EEMUA recommendations overly aggressive, or are they justifiable with respect to human performance limits?"

How fast can an operator respond to an alarm?

Approach to Answering “the Question”

- We made two different attempts at answering this question
  - The first was an analytical Keystroke-Level Modeling (KLM) analysis (Kieras, 2001)
  - The second was a Markov modeling analysis (Kemeny & Snell, 1976)

KLM Analysis – Assumptions on Time

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- **Times associated with various GOMS operators** (Kieras, 2001)
  - **Mental act,** **0.5-1.35 sec (Avg. 1.2)**
  - **Eye movement,** **0.03 sec**
  - **Perceive binary info** (e.g., icon) **0.1 sec**
  - **Perceive complex i**
  - **Execute one Key St**
  - **Execute Key Stroke**
  - **Mouse Point,**
  - **Hand movement,**

Assumption	Value
DCS Graphical Display Page Call-up Time	2.0 sec
Alarm Summary Page Call-upTime	0.25 sec
Process lag in response to control input	30 sec
Alarm resolution lag	60 sec
Number of key presses per alarm to affect change in system	3
Old event size (number of alarms *validated* in the alarm summary display, i.e., standing alarms)	10 alarms
New event size (number of simultaneous alarms initially *NOT validated* in the alarm summary display)	1-30 alarms

KLM Analysis – Assumptions on Joint Cognitive System Behavior

Assumption	Qualitative Validity
The operator using the TDC 3000 is an expert who is trained and capable of ***error-free recall*** of required actions for a given alarm.	**Moderate**
The Alarm Summary display is **continuously present** on a dedicated screen.	**Strong**
Alarms are **displayed in chronological order** (as opposed to alarm priority).	Moderate
Alarm priority is **indicated redundantly through both visual and auditory** coding.	**Strong**
Alarms are independent, each requiring specific actions to resolve.	***Weak***
Prior to alarm coming in, the operator is **attentively engaged and monitoring** the TDC.	**Moderate**
Prior to alarm coming in, the **operator is NOT looking directly at the Alarm Summary display**.	**Strong**
The operator **responds immediately** to an incoming alarm.	**Strong**

KLM Analysis Results – Model Structure

KLM Model

Super GOAL: Respond to notification of alarm

- **GOAL 1.0: Assess notification**
  - **GOAL 1.1.0: Perceive and process alarm**
  - **GOAL 1.2.0: Validate alarm**
  - **GOAL 1.3.0: Determine cause for alarm**
- **GOAL 2.0: Determine appropriate action**
  - **GOAL 2.1: Choose control movement**
  - **GOAL 2.2.0: Verify preconditions**
- **GOAL 3.0: Execute action**
  - **GOAL 3.1: Locate control**
  - **GOAL 3.2: Affect control**
- **GOAL 4.0: Determine effect of action**
  - **GOAL 4.1.0: Verify change of state**
  - **GOAL 4.2.0: Establish alarm state**
  - **LOGIC 4.0: IF(**alarms remain to be resolved**) THEN**
    - Iterate **GOAL 2.0**
    - Iterate **GOAL 3.0**
    - Iterate **GOAL 4.0**
  - Total alarm resolution lag (time waiting for alarm state to

GOMS Model	*Logic*	*Modifier*	*Code*	*(seconds) Est. Time*
Super GOAL: Respond to notification of alarm				**201.56**
GOAL 1.0: Assess notification				**44.74**
GOAL 1.1.0: Perceive and process alarm				**12.83**
GOAL 1.1.1: Orient to the Alarm Summary Page				**2.04**
GOAL 1.1.1.1: Silence auditory signal				**0.71**
GOAL 1.1.2.0: Search for newest, highest priority alarm				**9.92**
GOAL 1.1.2.1: Visual Search				**3.92**
LOGIC 1.1.2.1: IF (new alarm NOT on current Alarm Summary Page**) THEN**	***0.00***	*1.00*	M	1.20
Iterate **GOAL 1.1.2.1**				**0.00**
GOAL 1.1.2.2: Establish priority of alarm				**3.60**
LOGIC 1.1.2: IF (more new events discovered**) THEN**	***0.00***	*1.00*	M	1.20
Iterate **GOAL 1.1.2.1**				**0.00**
Iterate **GOAL 1.1.2.2**				**0.00**
GOAL 1.1.3: Read alarm line				**0.87**
GOAL 1.2.0: Validate alarm				**19.91**
GOAL 1.2.1.0: Establish point value				**16.31**
GOAL 1.2.1.1: Read variable value				**15.08**
LOGIC 1.2.1.1: IF (point value NOT on current System Page**) THEN**	***0.00***	*1.00*	M	1.20
LOGIC 1.2.1.2: IF (point value needs more detail from current System Page**) THEN**	***0.00***	*1.00*	M	1.20
LOGIC 1.2.1: IF (points remain to be reviewed**) THEN**	***0.00***	*1.00*	M	1.20
Iterate **GOAL 1.2.1.0**				**0.00**
GOAL 1.3.0: Determine cause for alarm				**12.00**
GOAL 1.3.1: Establish criticality of alarm				**7.20**
LOGIC 1.3.1: IF (alarm value does NOT exceed critical limit**) THEN**	***0.00***	*1.00*	M	1.20
GOAL 1.3.2: Establish cause of alarm (target or process change?)				**4.80**
LOGIC 1.3.2: IF (alarms remain to be validated**) THEN**	***0.00***	*1.00*	M	1.20
Iterate **GOAL 1.0**				**0.00**
GOAL 2.0: Determine appropriate action				**21.11**
GOAL 2.1: Choose control movement				**4.80**
GOAL 2.2.0: Verify preconditions				**15.11**
GOAL 2.2.1.0: Establish point value				**13.91**
GOAL 2.2.1.1: Read variable value				**12.68**
LOGIC 2.2.1.1: IF (point value NOT on current System Page**) THEN**	***0.00***	*1.00*	M	1.20
LOGIC 2.2.1.2: IF (point value needs more detail from current System Page**) THEN**	***0.00***	*1.00*	M	1.20
LOGIC 2.2.1: IF (precondition SATISFIED**) AND (**points remain to be reviewed**) THEN**	***0.00***	*1.00*	M	1.20
Iterate **GOAL 2.2.1.0**				**0.00**
LOGIC 2.2.2: IF (ALL necessary points SATISFY precondition**) AND (**preconditions remain to be reviewed**) THEN**	***0.00***	*1.00*	M	1.20
Iterate **GOAL 2.2.0**				**0.00**
LOGIC 2.2.3: IF (precondition NOT satisfied**) THEN**	***0.00***	*1.00*	M	1.20
Iterate **GOAL 2.1**				**0.00**
GOAL 3.0: Execute action				**12.93**
GOAL 3.1: Locate control				**2.50**
LOGIC 3.1: IF (control NOT on current System Page**) THEN**	***0.00***	*1.00*	M	1.20
Iterate **GOAL 3.1**				**0.00**
GOAL 3.2: Affect control				**9.20**
LOGIC 3.2: IF (action NOT complete**) THEN**	***2.00***	*3.00*	M	3.60
Iterate **GOAL 3.2**				**3.40**
GOAL 4.0: Determine effect of action				**122.78**
GOAL 4.1.0: Verify change of state				**40.31**
GOAL 4.1.1.0: Establish point value				**39.11**
GOAL 4.1.1.1: Read variable value				**5.48**
LOGIC 4.1.1.1: IF (point value NOT on current System Page**) THEN**	***0.00***	*1.00*	M	1.20
LOGIC 4.1.1.2: IF (point value needs more detail from current System Page**) THEN**	***0.00***	*1.00*	M	1.20
GOAL 4.2.0: Establish alarm state				**21.27**
GOAL 4.2.1: Visual Search for target alarm(s)				**2.72**
LOGIC 4.2.1: IF (target alarm NOT on current Alarm Summary Page**) THEN**	***0.00***	*1.00*	M	1.20
Iterate **GOAL 4.2.1**				**0.00**
GOAL 4.2.2.0: Identify alarm state				**16.12**
LOGIC 4.2.2: IF (alarm state has changed**) THEN**	**1.00**	*2.00*	M	2.40
GOAL 4.2.2.1.0: Verify new state is within operating limits (target or process within limits?)				**12.42**
GOAL 4.2.2.1.1: Read variable value				**5.19**
LOGIC 4.2.2.1.1.1: IF (point value NOT on current System Page**) THEN**	***0.00***	*1.00*	M	1.20
LOGIC 4.2.2.1.1.2: IF (point value needs more detail from current System Page**) THEN**	***0.00***	*1.00*	M	1.20
LOGIC 4.2.2.1: IF (points remain to be viewed**) THEN**	***0.00***	*1.00*	M	1.20
Iterate **GOAL 4.2.2.1.0**				**0.00**
LOGIC 4.2.0: IF (more alarms affected by action remain to be found**) THEN**	***0.00***	*1.00*	M	1.20
Iterate **GOAL 4.2.0**				**0.00**
LOGIC 4.0: IF(alarms remain to be resolved**) THEN**	***0.00***	*1.00*	M	1.20
Iterate **GOAL 2.0**				**0.00**
Iterate **GOAL 3.0**				**0.00**
Iterate **GOAL 4.0**				**0.00**
Total alarm resolution lag (time waiting for alarm state to change)		*1.00*	AL	60.00

KLM Analysis Results – Time Estimates

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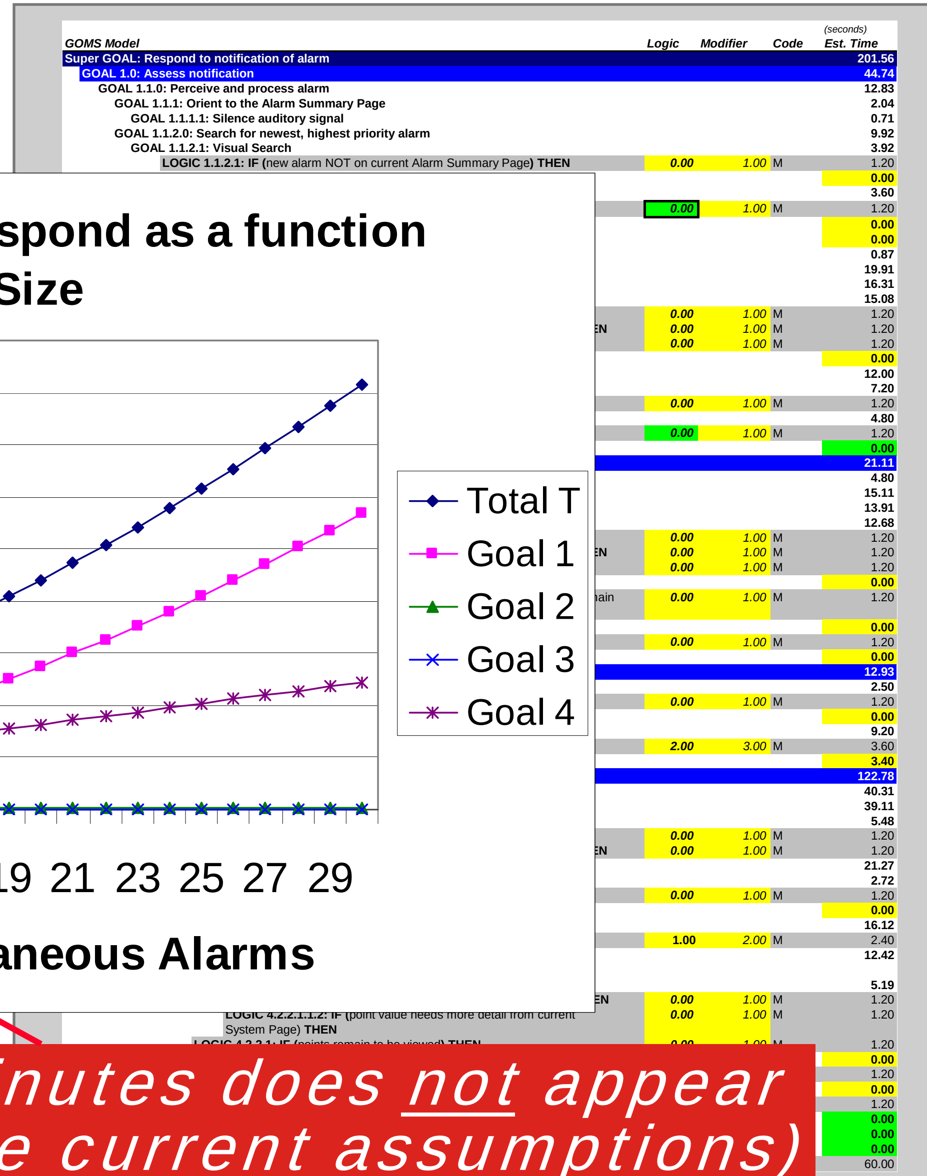

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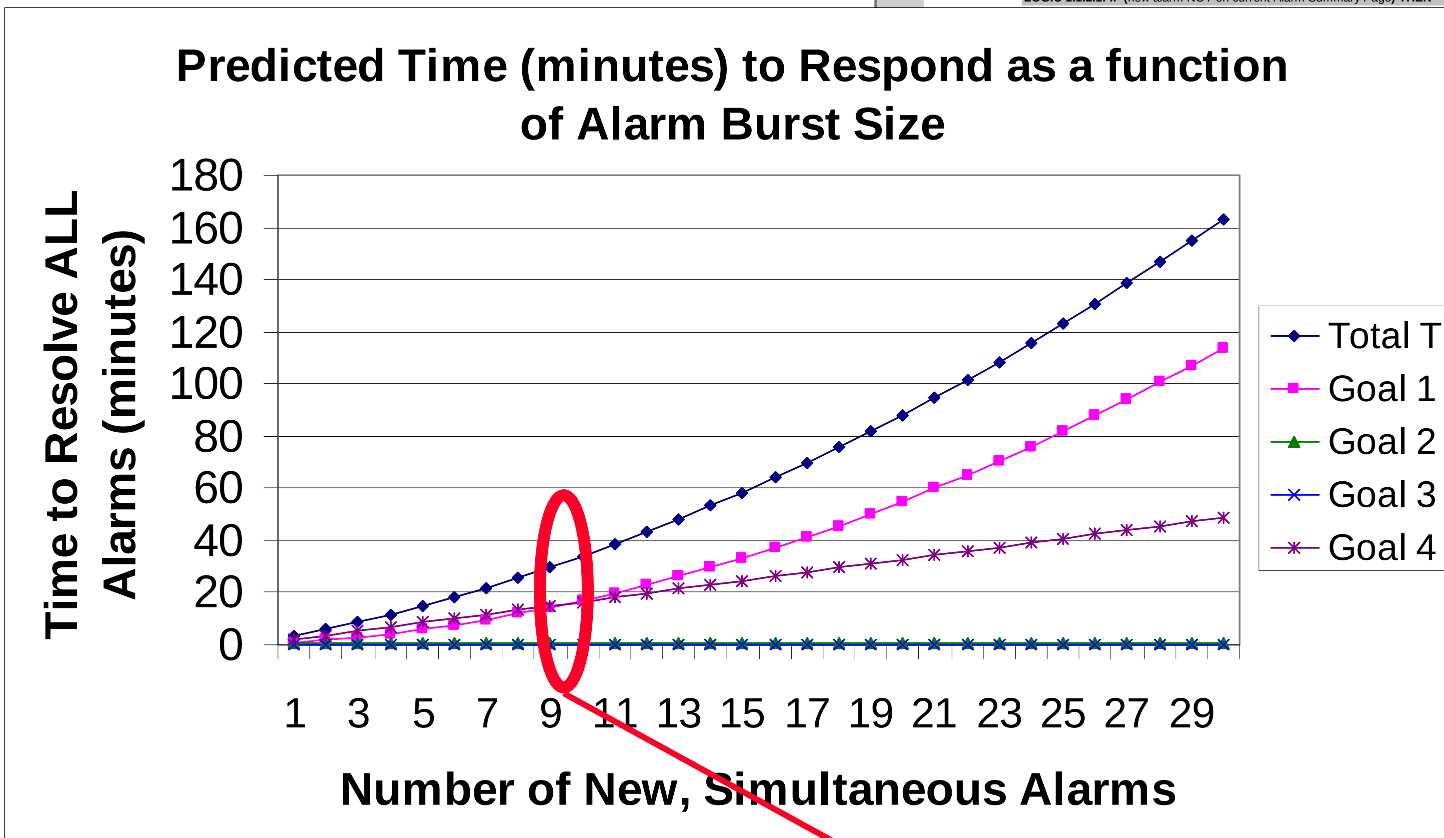

10 alarms per 10 minutes does not appear reasonable (with the current assumptions)

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Markov Modeling Analysis – Characterizing Observed Operator Response

- **Conducted observational study at an ASM operating company member site**
- **Video-recorded operators during simulator training**
  - **Three different process units were included**
  - **In total, five (5) operators participated in the observations/ video recording**
    - Avg. time in current position: 1.6 years
    - Avg. industry experience: 12.3 years
  - **Each operator participated in ~5 scenarios – *similar across units, but not identical* – totaling ~1 hour per operator**
    - Prototypical scenarios: tripped reflux pump, failed valve open (or close), turbo expander trip, pump interlock trip, condensate fan & pump trips with interlocks (one scenario)
    - Asked console operator to behave as s/he would at the console
    - Concluded scenario when Trainer and Operator agreed that process was under control
      - e.g., stabilized and ready to initiate a recovery procedure or re-setting equipment changes done to stabilize

Markov Modeling Analysis – Encoding videotaped Behavior

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Activity Code for Process Trace
AL: Alarm comes in
SA: Silences horn
LA: Looks at alarm summary page
LD: Looks at process display
ND: Navigates to new process display
BM: Makes a board move
RQ: Makes a request to the field
FO: Field operator communication
FU: Console follow up communication
AC: Acknowledge Field Action
BA:“Banter”
PC: Participant comment (to self)
CA: Clear alarm summary page
ES: End of Scenario

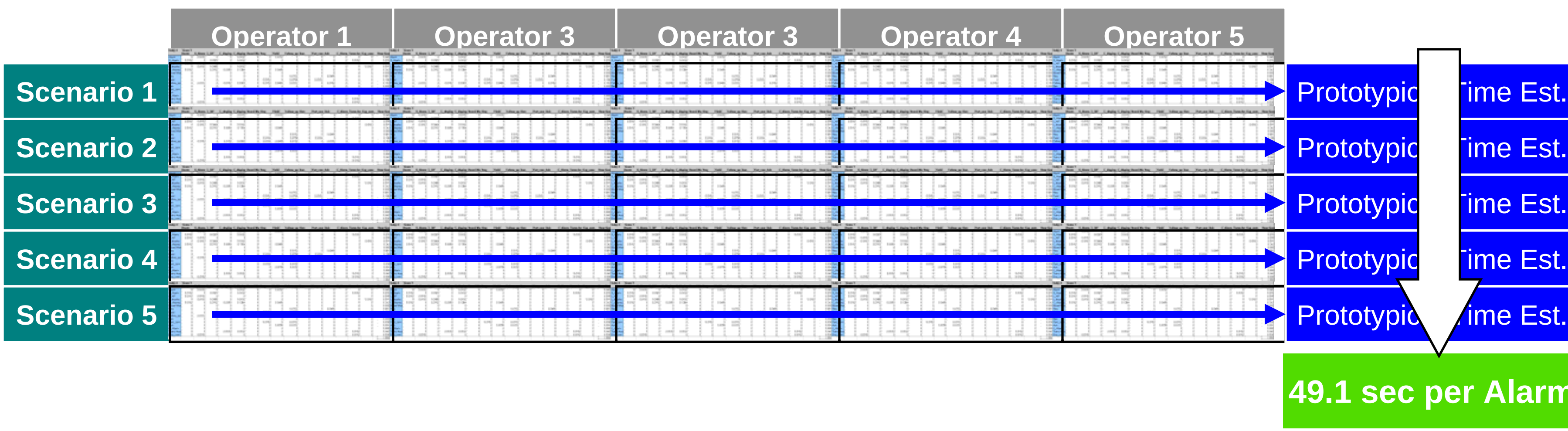
Scenario	Time Start	Time End	Event	No. of new alarms	Comments
[…]					
1	1.01		TS		
1	1.15		AL	1	
1	1.17		SH		
1	1.22		ND		
1	1.26		ND		
1	1.27		LD		
1	1.33	1.36	RQ	1	P: K, I need you to go check the 321 pump please
1	1.36		SA		
1	1.4		ND		
1	1.44		AL	1	
1	1.59		FO		
1	2.00	2.02	RQ	2	P: Both pumps are down? Well could you start one up please
[…]					

Markov Modeling Analysis – Averaged Transition Probabilities and "Dwell Times"

- **Calculated 'state' transitions probabilities for each scenario**

Subj: 4	Scen: 1															
	Alarm	S_Alarm	L_AP	L_display	C_display	Board Mo	Req	Field	Follow_up	Ban	Part_com	Ack	C_Alarm	Turns Arc	Exp_com	Row Sum
Alarm	0	0.0152	0	0	0.0152	0	0	0.0152	0	0	0	0	0	0	0	0.045
S_Alarm	0.0152	0	0.0303	0	0.0152	0	0	0	0	0	0	0	0	0.0152	0	0.076
L_AP	0.0152	0.0152	0	0	0	0	0	0	0	0	0	0	0	0	0	0.030
L_display	0	0.0152	0.0455	0	0.0152	0	0	0	0	0	0	0	0	0	0.0152	0.091
C_display	0.0152	0	0.0152	0.0303	0.1364	0	0	0.0455	0	0	0	0	0	0	0	0.242
Board Mov	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.000
Req	0	0	0	0	0	0	0	0	0.0152	0	0	0.0455	0	0	0	0.061
Field	0	0	0	0	0	0	0.0152	0	0.0758	0	0.0152	0	0	0	0	0.106
Follow_up	0	0.0152	0	0.0152	0.0303	0	0.0152	0.0455	0.0152	0	0	0.0152	0	0	0	0.152
Ban	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.000
Part_com	0	0	0	0	0	0	0.0152	0	0.0152	0	0	0	0	0	0	0.030
Ack	0	0	0	0	0	0	0	0.0758	0.0152	0	0	0	0	0	0	0.091
C_Alarm	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.000
Turns Arou	0	0	0	0.0152	0.0152	0	0	0	0	0	0	0	0	0.0152	0	0.045
Exp_com	0	0.0152	0	0	0	0	0	0	0	0	0	0	0	0.0152	0	0.030
																1.000

- **Calculated probabilistic time averages (based on average dwell times of each state and the probability of being in that state) for each scenario**



Markov Modeling Analysis – Time Estimate

- Given 49.1 seconds, which is approximately 80% of a minute
- And given Parks & Boucek (1988), whose work suggests not overloading an operator more than 80% of the time
- It would appear that EEMUA's recommendation of less than 10 alarms per 10 minute period following an upset condition are legitimate
  - At the very least, it could be considered the upper limit on human performance with today's alarm system technology
  - And today's process industry should be striving to achieve those recommendations

Qualifications/Improvement Opportunities to the Markov Modeling

- The trainer *approximated* the communications between field and console
  - Anecdotal sharing suggests that the times were shorter in the simulator training than they would be in practice.
- Establish the duration (e.g., 10 minutes, 10 hours, 10 days) that an operator could maintain the pace of one alarm every 49 seconds

10 alarms per 10 minute is very likely the ceiling on operator response performance

Qualifications/Improvement Opportunities to the KLM

- Add and elaborate on interaction with Field Operators to improve sub-tasks and subsequent time estimates
- Address the assumption that operators immediately engage in knowledge-based behavior (Rasmussen, 1986)
- Account for operator expectation of sets of alarms (cf., Kragt & Bonten, 1983).
- Account for parallel activity, as observed in the observations for the Markov Modeling efforts

Practical Implications

- Use of sophisticated alarm management techniques could be applied to aid the operator in assessing the notification (i.e., Goal 1 of the KLM model)
  - e.g., alarm filtering or modal alarming (O'Hara et al, 1994)
- Perhaps most significantly, to achieve peak alarm rate targets, there is a need to
  - (1) consider upset conditions as part of the alarm rationalization processes
    - asking how a given point will contribute to either the understanding of the upset or to the alarm flood that might be associated with the event, and
  - (2) analyze alarm system performance as part of incident investigations when incidents or accidents do occur to determine if alarm configuration improvements are needed

Future Research

- **Improve the validity of the KLM and its predictive worth**
  - **Relate the observed behavioral sequences coded for the Markov Analysis back to the analytical KLM elements**
    - We are currently investigating to what extent sequential analysis techniques (Bakeman & Gottman, 1997) can be applied to relating the observed behavior sequences to those in the KLM
- **Other future work related to human response to alarm notifications includes:**
  - **Establish a duration for which a peak alarm rate of 10 alarms per 10 minute period remains acceptable**
  - **Conducting a more comprehensive observational study, across both the refining and petrochemicals industries, involving multiple companies, etc.**
    - To offset potential idiosyncrasies that might arise due to an individual site's training program, user interface design approach, alarm system sophistication, and so on.

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