

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

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- **“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

- **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)

- **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

- 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 info
 - Execute one Key Stroke
 - Execute Key Stroke
 - Mouse Point,
 - Hand movement,

Assumption	Value
DCS Graphical Display Page Call-up Time	2.0 sec
Alarm Summary Page Call-up Time	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 <i>validated</i> in the alarm summary display, i.e., standing alarms)	10 alarms
New event size (number of simultaneous alarms initially <i>NOT validated</i> 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

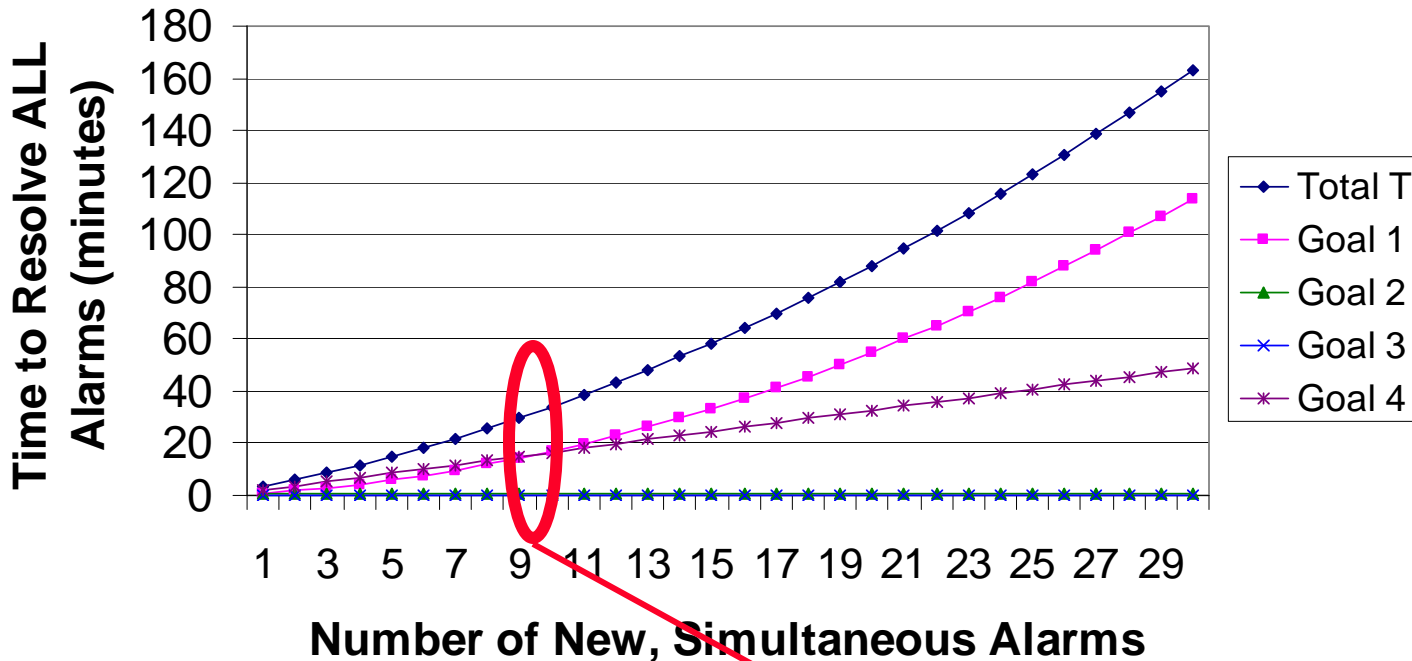
Total alarm resolution lag (time waiting for alarm state to

GOMS Model	Logic	Modifier	Code	Est. Time (seconds)
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 3.0				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

GOMS Model	Logic	Modifier	Code	Est. Time (seconds)
Super GOAL: Respond to notification of alarm				201.56
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				0.00
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	0.00	1.00	M	1.20
				0.00
				0.00
				0.87
				19.91
				16.31
				15.08
	0.00	1.00	M	1.20
	0.00	1.00	M	1.20
	0.00	1.00	M	1.20
				0.00
				12.00
				7.20
	0.00	1.00	M	1.20
				4.80
	0.00	1.00	M	1.20
				0.00
				21.11
				4.80
				15.11
				13.91
				12.68
	0.00	1.00	M	1.20
	0.00	1.00	M	1.20
	0.00	1.00	M	1.20
	0.00	1.00	M	1.20
				0.00
				12.93
				2.50
	0.00	1.00	M	1.20
				0.00
	0.00	1.00	M	1.20
				9.20
	2.00	3.00	M	3.60
				3.40
				122.78
				40.31
				39.11
				5.48
	0.00	1.00	M	1.20
	0.00	1.00	M	1.20
				21.27
	0.00	1.00	M	1.20
				2.72
				0.00
	1.00	2.00	M	2.40
				12.42
				5.19
	0.00	1.00	M	1.20
	0.00	1.00	M	1.20
				1.20
				0.00
				1.20
				0.00
				1.20
				60.00

Predicted Time (minutes) to Respond as a function of Alarm Burst Size



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

KLM Analysis – Assumptions on Joint Cognitive System Behavior

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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

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

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

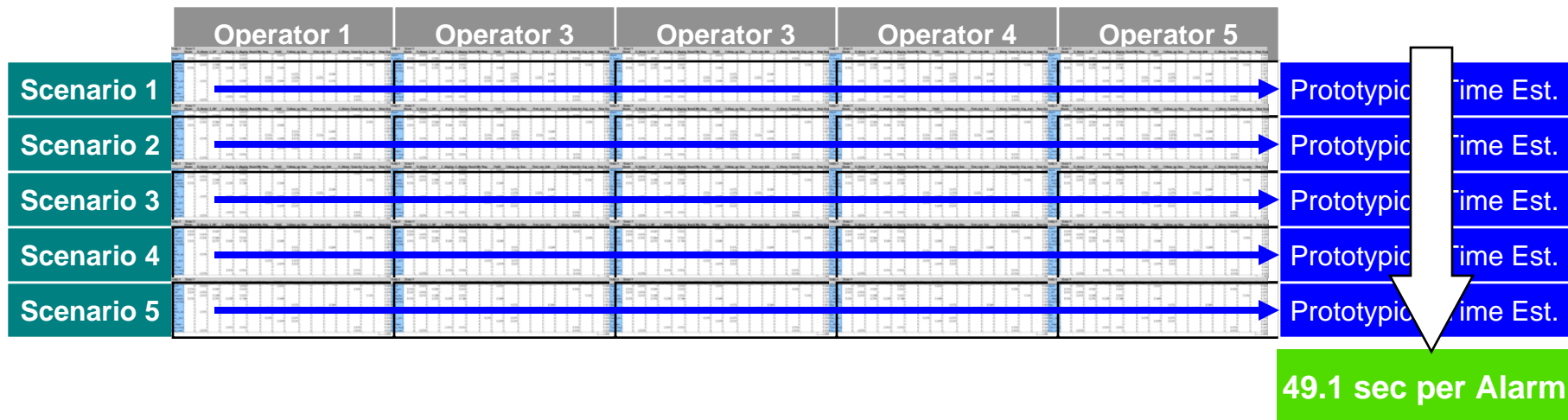
Scenario	Time Start	Time End	Event	No. of new alarms	Comments
[...]					
1	1.01		TS		
1	1.15		AL	1	
1	1.17		SH		
1	1.22		ND		
1	1.26		ND		
1	1.27		LD		
1	1.33	1.36	RQ	1	P: K, I need you to go check the 321 pump please
1	1.36		SA		
1	1.4		ND		
1	1.44		AL	1	
1	1.59		FO		
1	2.00	2.02	RQ	2	P: Both pumps 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															Row Sum
	Alarm	S_Alarm	L_AP	L_display	C_display	Board Mo	Req	Field	Follow_up	Ban	Part_cor	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	0.0455	0	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

- 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

- **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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