The EMBRACE Methodology for Human Reliability Analysis: An AI-Assisted Expert Evaluation of Its Support Software

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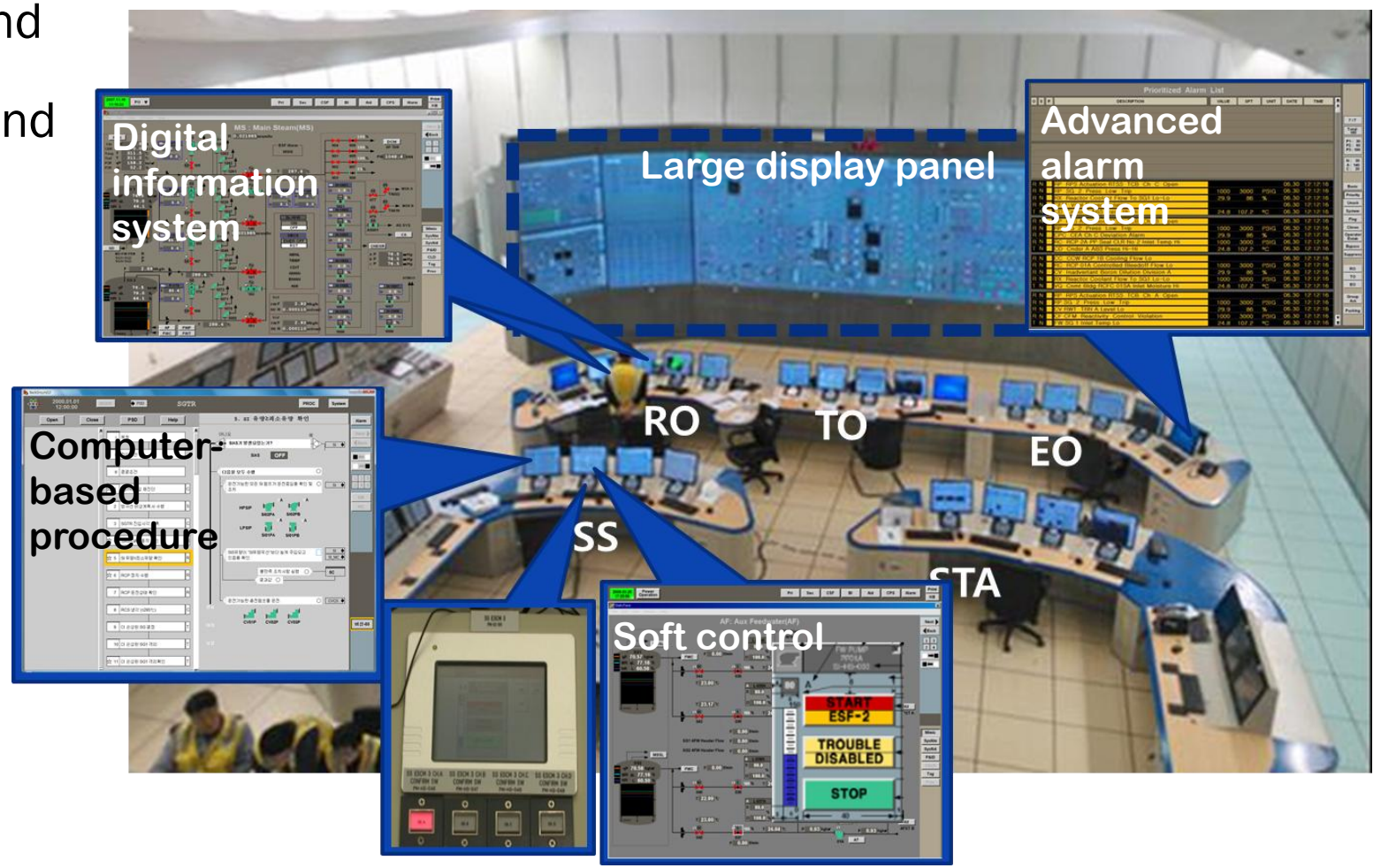
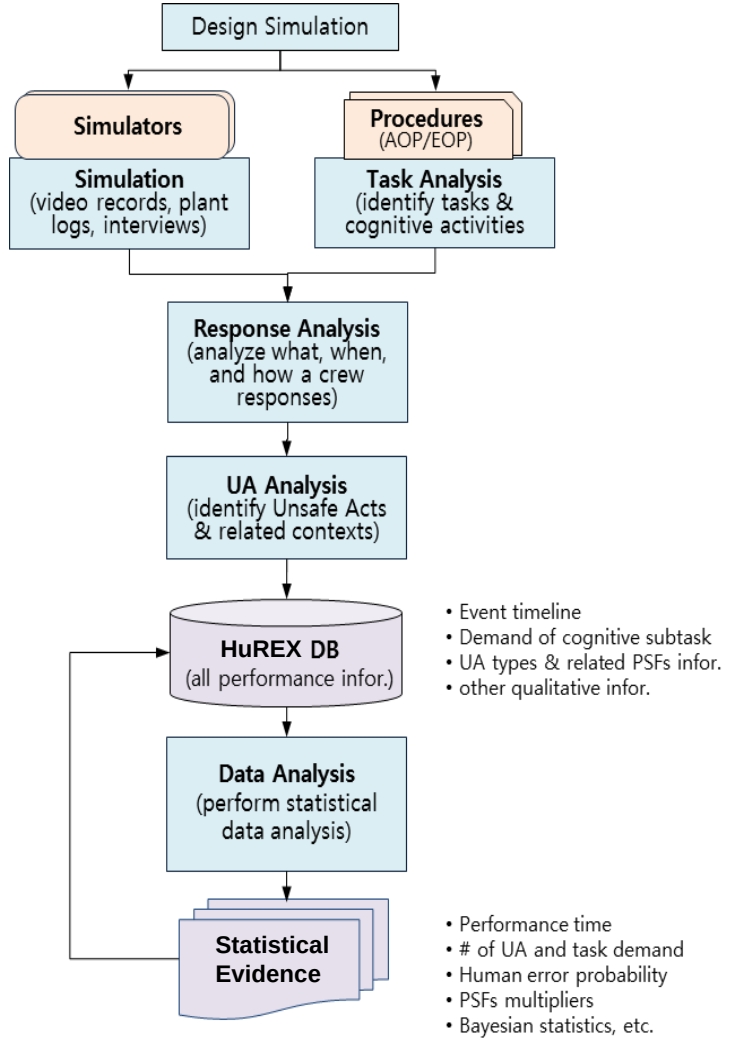
Computer-Based Control Room in APR1400

- Human performance issues
  - Instrumentation quality and complexity
  - Control interface quality and complexity
  - Situation awareness
  - Task complexity
  - Communication and coordination
  - Digital fatigue
  - Digital system failure
  - Recovery
  - Trust and reliance
  - Stress
  - Control interface quality



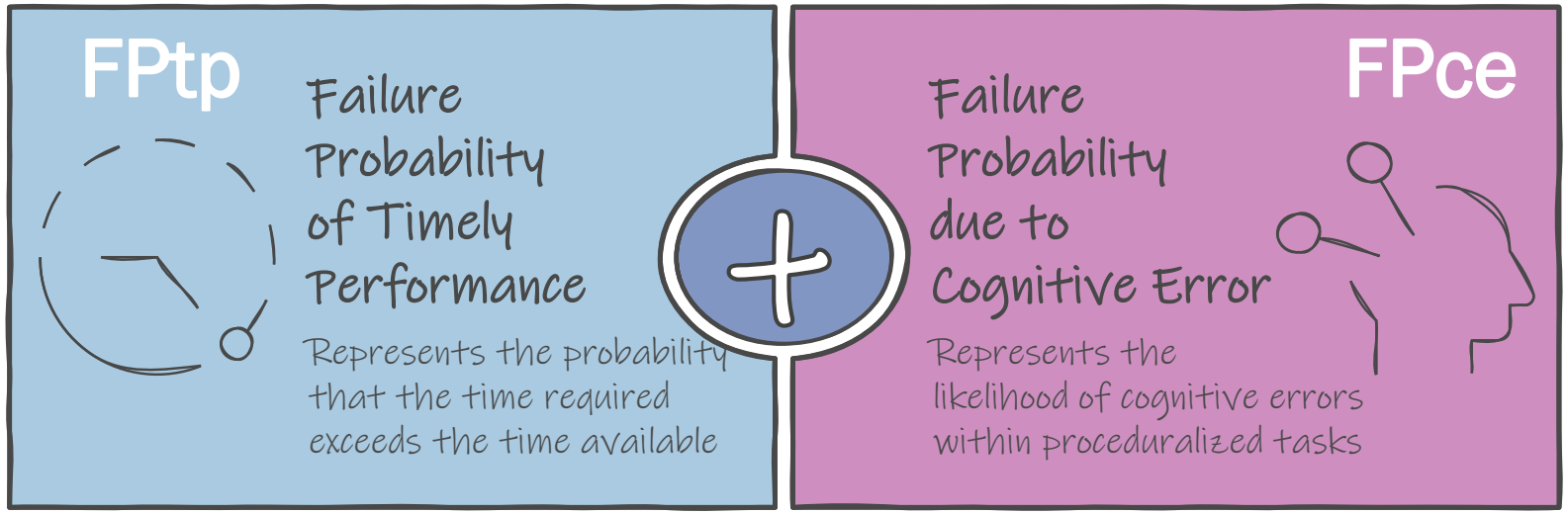
Development of a New HRA Method

- Realistic reliability estimates considering digital human factors issues
  - Empirical evidence supporting the quantitative reliability estimates
    - Human error probability (HEP)
    - Human performance time
    - Recovery failure probability
    - Dependency factors
    - Uncertainty bounds
    - …
- U.S. and international benchmarking projects (around 2010)
  - Methods relying on time–reliability curves may not be suitable for assessing diagnostic difficulty.
  - Many HRA methods do not adequately model the cognitive activities expected during scenario response.



EMBRACE Method

- EMBRACE (EMpirical data-Based crew Reliability Assessment and Cognitive Error analysis)
  - HEP = FPtp + FPce

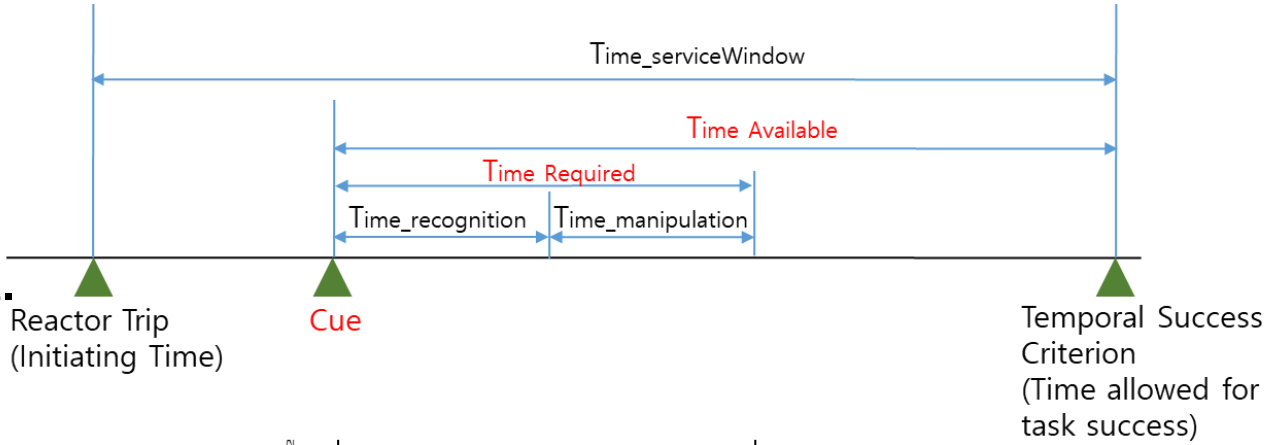


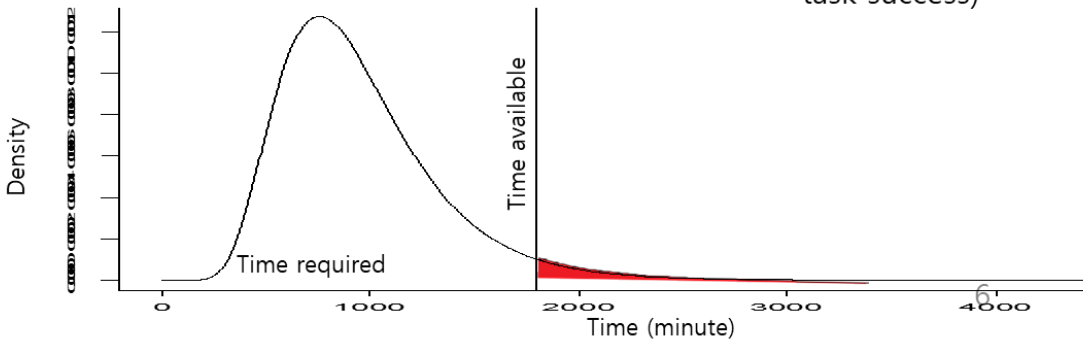
Failure Probability of Timely Performance (FPtp)

- FPtp
  - Prob [time required (T_r) > time available (T_a)]
- Time available (T_a)
  - Determined by thermal-hydraulic analysis or expert judgment.
  - Usually applied as a point estimate
- Time required(T_r)
  - Estimated from simulation data.
  - Human performance time typically follows a log-normal distribution.

  → FPtp = 1 - Φ [ln(Ta/Tr)/ σ]

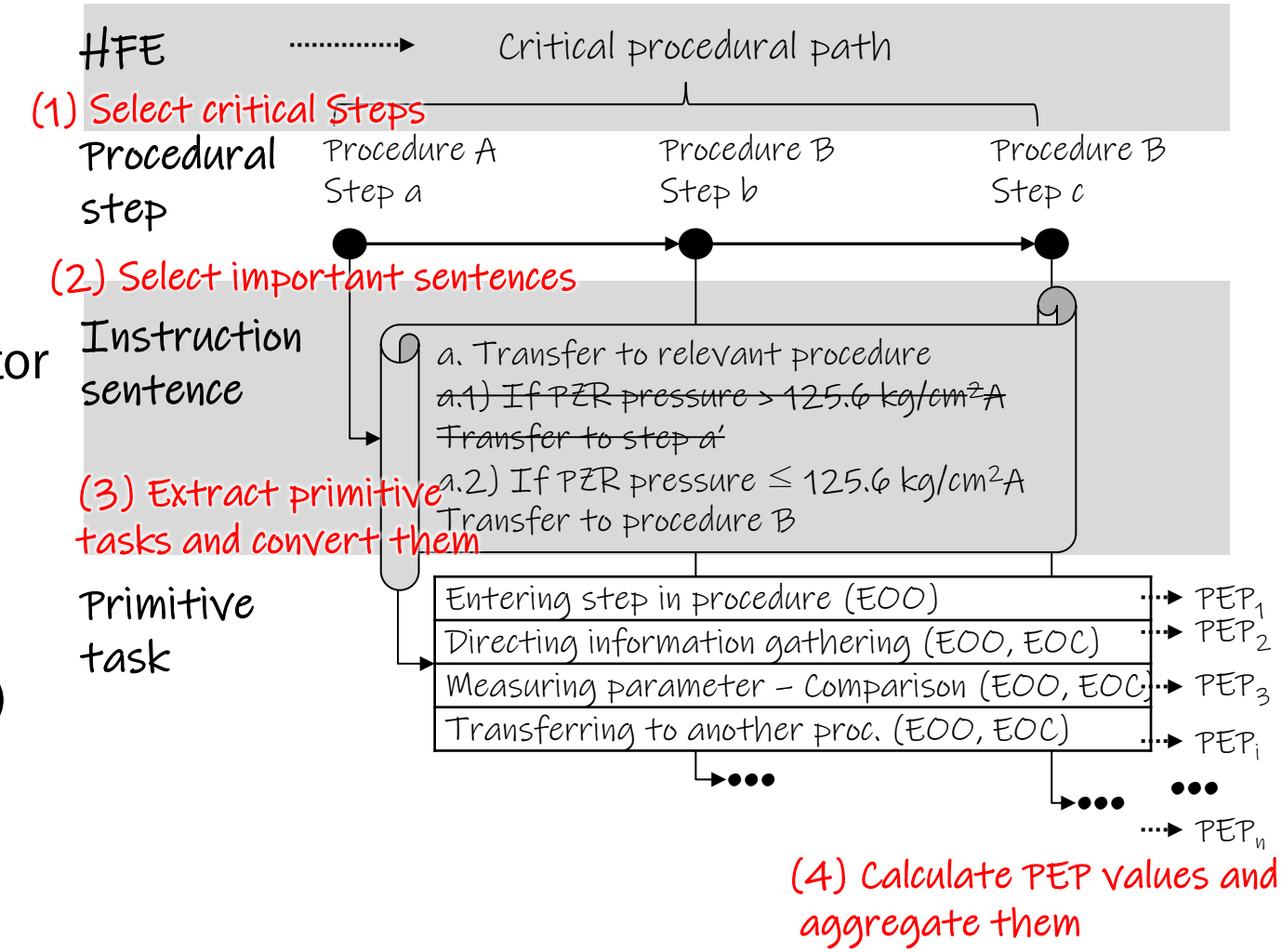
  σ = 0.3403





Failure Probability due to Cognitive Error (FPce)

- FPce = (ΣPEP) * PSFm * RFP
  - PEP (Primitive error probability)
    - Nominal HEP of primitive tasks
    - Statistical estimates from HuREX data
  - PSFm (Performance shaping factor multiplier)
    - Multiplier applied to the sum of PEPs
    - Estimates from expert elicitation
  - RFP (Recovery failure probability)
    - Estimated using traditional dependency rules



Nominal PEP Values

Cognitive activity	Primitive task type	Abbreviation	PEP (high exp.)
Information gathering and reporting (IG)	Verifying alarm occurrence	IG-alarm	1.10E-04
	Verifying state of indicator	IG-indicator	1.10E-04
	Synthetically verifying information	IG-synthesis	1.51E-03
	Reading simple value	IG-value	1.10E-04
	Comparing parameters	IG-comparison	1.10E-04
	Comparing in graph constraint	IG-graph	1.10E-04
	Comparing for abnormality	IG-abnormality	1.10E-04
	Evaluating trend	IG-trend	3.08E-04
Situation interpreting (SI)	Diagnosing	SI-diagnosis	2.16E-03
	Identifying current overall status	SI-identification	2.16E-03
	Predicting	SI-prediction	2.16E-03
Response planning and instruction (RP)	Entering the succeeding step in the procedure	RP-entry	1.85E-04
	Transferring to another proc.	RP-procedure	5.62E-03
	Transferring to step in the same procedure	RP-step	5.62E-03
	Directing information acquisition	RP-information	6.22E-05
	Directing (simple/dynamic) manipulation	RP-manipulation	1.96E-03
	Directing external notification/request	RP-notification	1.85E-04
Execution (EX)	Manipulation - Simple (discrete) control	EX-discrete	1.84E-03
	Manipulation - Simple (continuous) control	EX-continuous	1.53E-02
	Manipulation - Dynamic manipulation	EX-dynamic	1.49E-02
	Notifying/requesting outside the MCR	EX-notification	1.84E-03

PEP Aggregation (Example)

Step	ID	Sentence	Primitive task (#, PEP)	Sum
DA, 5	0	Goal: Check SG level	• RP-Entry (1, 3.38E-04)	1.22E-02
	1	Is the level of a SG lower than 30%? (if yes, go to step #9, otherwise, go to step #10 for the LOAF procedure)	• RP-Information (1, 2.35E-03) • IG-Comparison (1, 1.04E-04) • RP-Step (1, 9.45E-03)	
LOAF, 10	0	Goal: Check heat removal from SG	• RP-Entry (1, 6.76E-04)	2.94E-02
	1	Check if the SG level is lower than 1% & go to contingency action part if not satisfied	• RP-Information (1, 4.69E-03) • IG-Comparison (1, 4.16E-04) • RP-Step (1, 1.89E-02)	
	1(CA*)	Go to the 1st step of the FRP-#	• RP-Procedure (1, 4.69E-03)	
FRP-#, 7	0	Goal: Prepare feed and bleed	• RP-Entry (1, 6.76E-04)	1.79E-02
	1	Prepare the feed and bleed by performing the following:	-	
	1(1)	Verify the safety valves are operable	-	
	1(2)	Supply power to the safety valves	• RP-Notification (1, 6.76E-04) • EX-Notification (1, 1.21E-02) • EX-Local-Discrete (1, 4.47E-03)	
FRP-#, 9	0	Goal: Initiate feed and bleed	• RP-Entry (1, 6.76E-04)	1.84E-02
	1	If a leak alarm of safety valves has activated and discharge temperature exceeds 160 degrees	• RP-Information (1, 6.76E-04) • IG-Alarm (1, 8.31E-04) • RP-Information (1, 6.76E-04) • IG-Comparison (1, 8.31E-04)	
	2	Then, manually open the safety valves	• RP-Manipulation (1, 9.86E-03) • EX-Discrete (1, 4.79E-03)	

PSFm and RFP Estimates

- PSF multiplier (PSFm)
  - If any PSF state within a step is unfavorable, multiply the sum of PEPs by PSFm [(ΣPEP) x PSFm]
  - The estimates
    - by aggregating the opinions of 12 experts using Cooke's Classical method

PSF	Proc. Transfer	Manipulation
Complexity of required task	3	3
Subjective stress	5 (2.5 for FRP)	5 (2.5 for FRP)
Complexity of human-machine interface	3	5
Procedure quality	5	5
Support function of computer-based procedure	2	3
~~Crew dynamics~~	~~1~~	~~1~~
Communication level	2	2
Training level	5	3
Perceived importance	10	10

- Recovery sources
  - Shift change recovery
  - Recovery from apparent cue
  - Recheck in stable status
  - STA (shift technical adviser) monitoring recovery
  - Recovery by procedure
- Recovery failure probability (RFP)

Recovery sources	Dependency	RFP
Shift change recovery	Zero	0.016
Recovery from apparent cue	Zero	0.016
Recheck in stable status	Low	0.05
STA monitoring recovery (37 min)	Moderate	0.14
STA monitoring recovery (22 min)	High	0.5
Recovery by procedure	High	0.5

$$FPce = \sum_{j}^{step} \left[\left(\sum_{i}^{PT} PEP_{i,j} \right) \times \prod_{k}^{PSF} PSFM_{k,j} \right] \times \prod_{l}^{recovery} RFP_{l}$$

Dependency Assessment of Human Failure Events

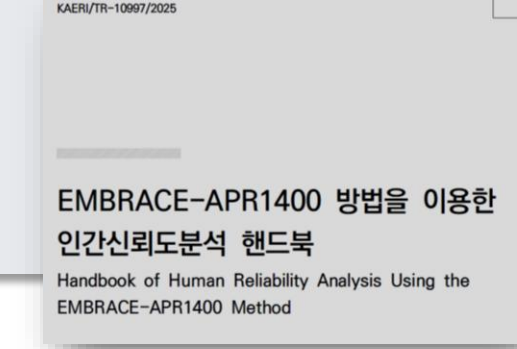
- Conditional HEP of Subsequent HFE

$$P(B|A) = [TRI + \{PTS + CRD\} * RF] * CS + P(B) * ACE_B$$

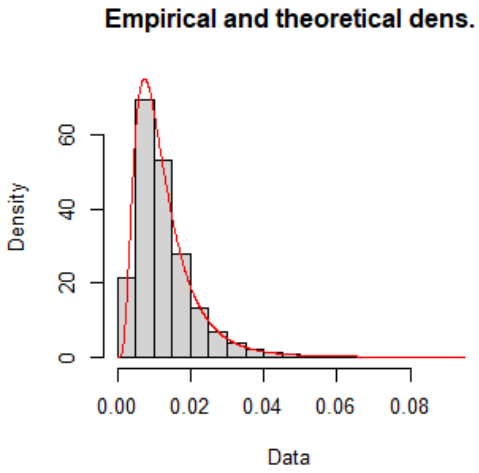
Feasibility
Mental Model
PIF change
Resource-sharing

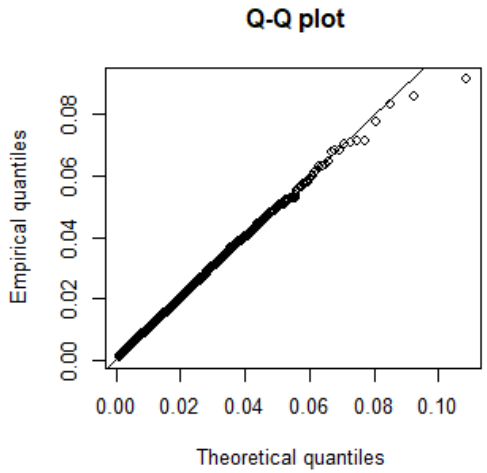
- TRI (Temporal resource insufficiency)
  - The probability that the performance times for the two HFEs overlap
- PTS (Procedure transition similarity)
  - The similarity between the two procedure flows (using a sequence alignment algorithm)
- CRD (Cue recognition dependency)
  - 0: different cues; 0.5: identical or very similar cues
  - The similarity between the instrumentation cues that trigger the two HFEs
- RF (Recovery factor)
  - 0.5: recoverable; 1: unrecoverable
  - The recoverability when *HFE A* has insufficient time while *HFE B* has sufficient time
- CS (Crew sameness)
  - 0: different crews; 1: same crew
  - Whether the same crew is involved in both events
- ACE (Additional context effect)
  - Whether *HFE A* elevates the stress or task complexity level for *HFE B*

Parameter Uncertainty Calculation



- Monte-Carlo simulation to understand the distribution of HEPs
  - The lognormal distribution best explains the HEPs across all cases.



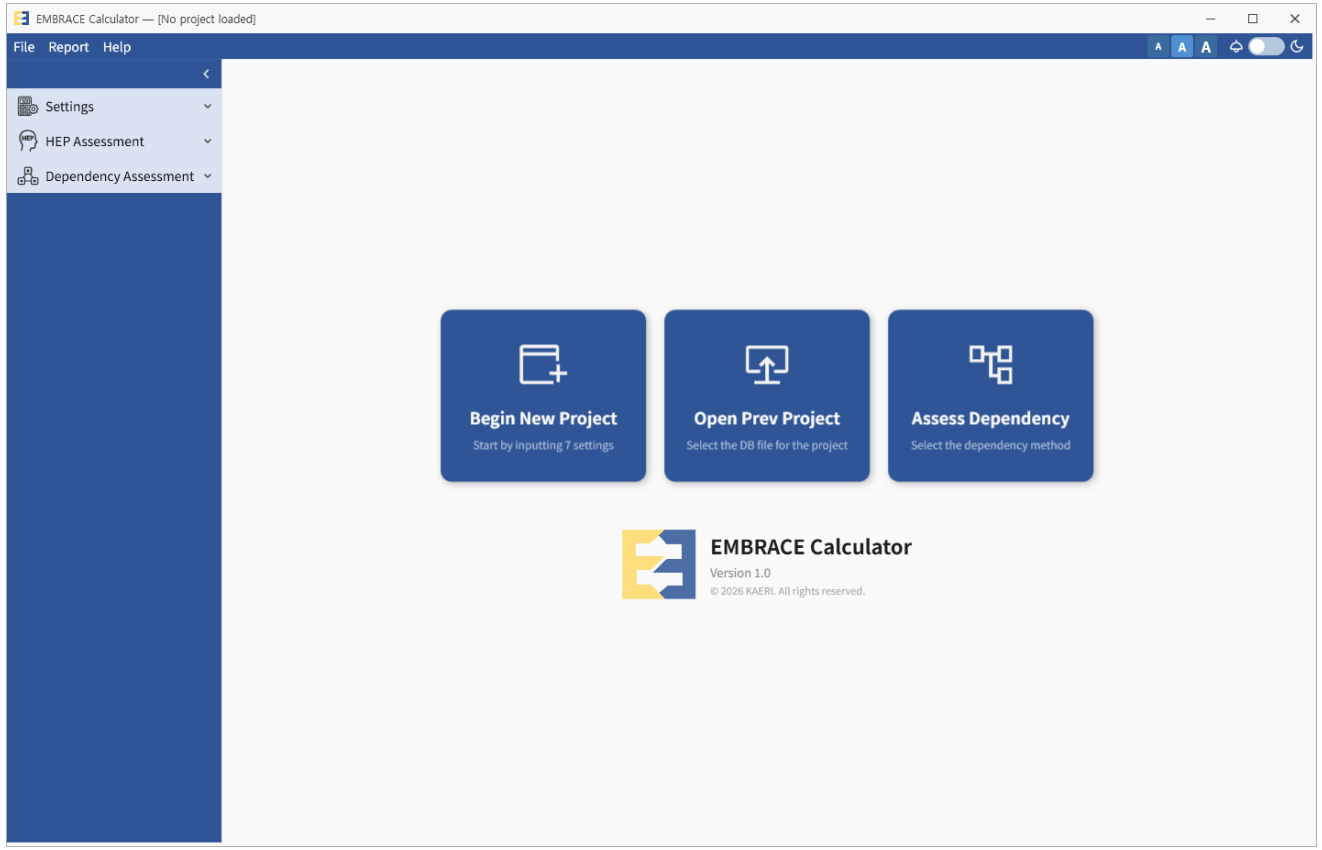


- Uncertainty bounds of HEP can be represented by error factors.
  - Generally, as an HEP decreases, its error factor increases.

HEP range	Error factor
0.5 ≤ HEP	1
0.03 ≤ HEP < 0.5	3
0.01 ≤ HEP < 0.03	4
0.006 ≤ HEP < 0.01	5
0.001 ≤ HEP < 0.006	7
HEP < 0.001	10

EMBRACE-Support Software (ESS)

- ESS aids HEP calculation using the EMBRACE framework.
  - Automates the retrieval of empirical data and procedure data
    - Procedure structure
    - Procedure sentences & tasks
    - PEP values
    - PSF multipliers
    - Basic human performance time
  - Visualizes cue timelines and procedural flows
  - Executes probabilistic algorithms for both FPtp and FPce
  - Automates analysis report generation



EMBRACE Calculator — [EMBRACE_Project_20260428_work.db]

File Report Help

Settings

HEP Assessment

EMBRACE method

Dependency Assessment

EMBRACE method

EMBRACE method

Search Option

HFE Input text

HEP Input numbe ~ Input numbe

FPtp Input numbe ~ Input numbe

FPce Input numbe ~ Input numbe

Proc Input text (e.g. SPTA, FRP)

Search

HFE list

	HFE Name	HEP	FPtp
▸	**Case1: p...**	**1.94E-02**	**1.3**
	Example...	2.67E-02	4.6
	Case2: p...	3.82E-01	8.3
	Pressure...	1.77E-03	1.6
	Example	1.68E-02	0.0
	Example2	3.10E-02	2.8

New Delete Duplicate

Basic Info FPtp FPce

Undo Redo

Basic Information

HFE ID: 202602200729-003

Project Name: RELab-KAERI evaluation

Plant Name: APR1400

HFE Name: Case1: poilot valve open

Description: During loss of all supply water, the operator open the motor-operated pilot valve by following FRP procedure.

Analyst: Yochan

Analysis Date: 2026-02-20

Reviewer: youngsuh

Review Date: 2026-03-05

Result

Calc: (•) Sum (FPtp + FPce) ( ) Union (FPtp + FPce - FPtp * FPce) ( ) Max (FPtp, FPce)

HEP: 1.94E-02

FPtp: 1.34E-02 FPce: 6.01E-03

Cognitive HEP: 1.75E-02 Executive HEP: 1.85E-03

Lowest assumed: 1.00E-05 Final HEP: 1.94E-02

Parameter uncertainty

Uncertainty rule: EMBRACE rule (Lognormal distribution)

Error factor: 4

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	Example	1.68E-02	0.0
	Example2	3.10E-02	2.8

New Delete Duplicate

Basic Info | FPtp | FPce

HFE Name: Case1: poilot valve open

Time Unit: second / min / hour

Undo Redo

Time Standard: Reactor trip

Temporal Success Criterion: 65

Time Input Basis: Thermal-hydraulic analysis

	Cue Name	Instr. Cue	Instr. CueTime	Proc. Cue	Procedure	Step		Proc. CueTime	Exe?	Execution Period	
▸	SG depletion	☑	25	☑	LOAF	10	▶	15.9	☐	0	⋮
	Relief valve power	☐	0	☑	FRP-CC	3	▶	3	☑	5	⋮
	Relief valve open	☑	30	☑	FRP-CC	8	▶	5	☑	1	⋮
*		■		■			▶		■		⋮

FPtp Detail

Distribution: Lognormal / Normal

Sigma: 0.3403

Value: 0.3403

Calculate FPtp

Cue #	Cue Name	Key Cue	Procedure re-open	Completion Time
1	SG depletion	Procedure	False	25
2	Relief valve power	Procedure	False	33
3	Relief valve open	Procedure	False	39

Result

Reference Cue: SG depletion RCT: 15.9 Treq: 23.1 Tavail: 49.1 FPtp: 1.34E-02

Draw Graph

Graph

Cue 3 33 39

EMBRACE Calculator — [EMBRACE_Project_20260428_work.db]

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EMBRACE method

Dependency Assessment

EMBRACE method

EMBRACE method

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	Pressure...	1.77E-03	1.6
	Example	1.68E-02	0.0
	Example2	3.10E-02	2.8

New Delete Duplicate

Basic Info | FPtp | FPce

Relief valve open	☑	30	☑	FRP-CC	8	▶	5	☑	1
*	■		■			▶		■	

FPtp Detail

Distribution ◉ Lognormal ○ Normal Sigma 0.3403 Value 0.3403 Calculate FPtp

Cue #	Cue Name	Key Cue	Procedure re-open	Completion Time
▸ 1	SG depletion	Procedure	False	25
2	Relief valve power	Procedure	False	33
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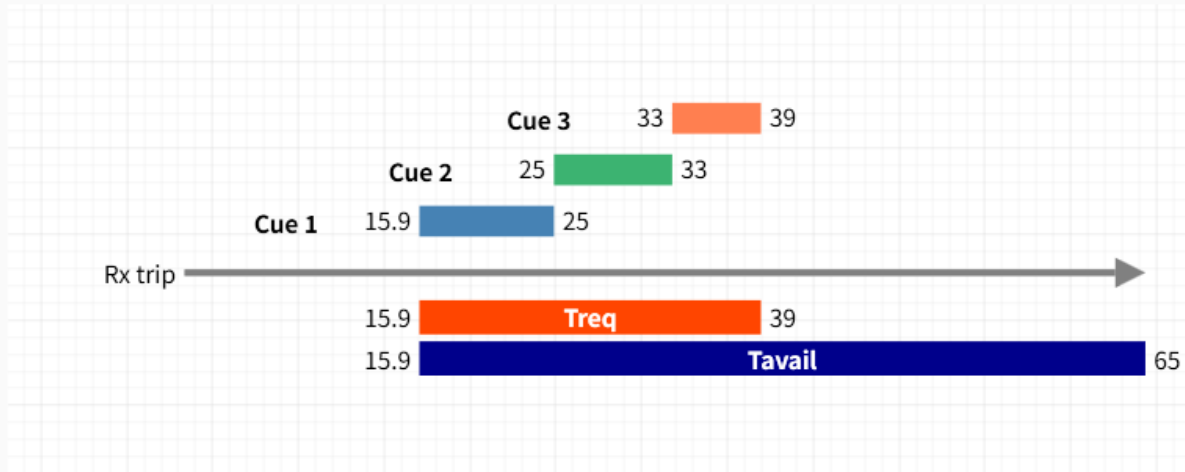
Result

Reference Cue SG depletion RCT 15.9 Treq 23.1 Tavail 49.1 FPtp 1.34E-02 Draw Graph

Graph



EMBRACE Calculator — [EMBRACE_Project_20260428_work.db]

File Report Help

EMBRACE method

Menu

EMBRACE method

Search Option

HFE Input text

HEP Input number ~ Input number

FPtp Input number ~ Input number

FPce Input number ~ Input number

Proc Input text (e.g. SPTA, FRP)

Search

HFE list

	HFE Name	HEP	FPtp
▸	Case1: poi...	1.94E-02	1.3
	Example ca...	2.67E-02	4.(
	Case2: poil...	3.82E-01	8.3
	Pressure c...	1.77E-03	1.(
	Example	1.68E-02	0.(
	Example2	3.10E-02	2.8

New Delete Duplicate

Basic Info FPtp FPce

HFE Name Case1: poilot valve open

Start Step <Reactor trip> <Reactor trip>

Waypoint (1) LOAF 10

End Step FRP-CC 8

Undo Redo

Generate Task Breakdown

Builds primitive task rows from the selected Start → End steps (including waypoints).

Procedure Flow and Primitive Tasks

<Reactor trip> → SPTA, 10 → DA, 1 → DA, 3 → FRP-1, 1 → FRP-1, 8 → FRP-CF, 1 → FRP-CC, 1 → FRP-CC, 8

Proc	Step	Important	SubStep	Content	TaskType	PEP	Perf. #	Step Sum	Step Type	PSF
SPTA	10	☐	0	Enter Emergency-01 (RT)	RP-Entry	1.85E-04	0	0.00E+00	Trans	Default
		☐	1	Are all safety function criteria met, and no actions take...	SI-Identification	2.16E-03	0			
		☐			RP-Step	5.62E-03	0			
		☐	2	Enter DA procedure.	RP-procedure	5.62E-03	0			
DA		☑	0	Verify Containment pressure trend	RP-Entry	9.25E-05	1	3.77E-03	Trans	Default
		☑			RP-Information	3.11E-05	1			
		☑		Is the containment pressure less than the safety limit and stable or decreasing?	IG-Comparison	5.50E-05	4			
		☑			IG-Trend	1.54E-04	4			
		☑			RP-Step	2.81E-03	1			
LOAF	10	☑	0	Verify adequacy of heat removal via Secondary Units	RP-Entry	1.85E-04	1	1.29E-02	Trans	Default

Add Row Delete Row Duplicate Row ■ Select all tasks as important

Recovery Failure Probability (RFP)

Crew/Cue/Procedure Recovery

☐ Shift change recovery (0.0164)

☐ Recovery from apparent cue (0.0164)

☐ Recheck in stable status (0.05)

STA Monitoring Recovery

◉ 1st attempt (22min<=Time margin<37min) (0.5)

○ 2nd attempt (Time margin>=37min) (0.14)

○ No credit (1)

Calculate FPce

Total PEP 2.40E-02

RFP 2.50E-01

FPce 6.01E-03

EMBRACE Calculator — [EMBRACE_Project_20260428_work.db]

File Report Help

Settings

HEP Assessment

EMBRACE method

Dependency Assessment

EPRI dependency method

EMBRACE dependency method

EMBRACE method | EMBRACE dependency method

EMBRACE Dependency

Search Option

Name Input text

Reference Input text

JHEP Input number ~ Input number

Search

	HFE Pair	JHEP	HEP (A)
▸	LOAF-sta...	1.27E-03	3.50E-0
	LOAF-sta...	8.01E-04	3.50E-0
	SGTR pre...	8.72E-04	1.90E-0

New Delete Duplicate

Import Export Undo Redo

CHEP(B)={TRI+(PTS+CRD)*RF}*CS+HEP(B)*ACE

ID 202603041831-001

HFE Pair Name LOAF-startup & F&B_more time margin

Remark Enter the text

Individual HEP (A) Ref Reference HFE Example case - Startup s

Individual HEP 3.50E-03

Initial time point 45

Time required (length) 11.1

Time available (length) 42

Procedure transition

DA_31, LOAF_6

Description During loss of all supply water, the operator start the startup supply pump.

Individual HEP (B) Ref Reference HFE Case1: poilot valve open

Individual HEP 2.61E-02

Initial time point 65

Time required (length) 23.1

Time available (length) 49.1

Procedure transition

DA_31, LOAF_10, FRP-CC_3, FRP-CC_8

Description During loss of all supply water, the operator open the motor-operated pilot valve by following FRP procedure.

Calculate CHEP

Crew Sameness (CS)

(●) Same ( ) Different

Temporal Resource Insufficiency(TRI)

Sigma value assumed

(●) 0.3403 ( ) 0.57 ( ) Else 0

TRI 3.41E-03

Procedure Transition Similarity (PTS) ?

Similarity score btw HFE (A) & (B) 1

Maximum similarity score 3 (A:[2], B:[4])

PTS 3.33E-01

Cue Recognition Dependency (CRD)

☑ Same cue location ☑ Same cue object ☐ No additional cue

CRD 0

Recovery Factor(RF)

☑ Crew review for HFE (A) recovery?

Time margin (A) 30.9 Time margin (B) 26.0

Demanded recheck time 70

RF 1

Additional Contextual Effect (ACE)

☐ Additional stress ☐ Increased task complexity

ACE 1

CHEP (B) 3.63E-01

HEP(A) * CHEP(B) 1.27E-03

EMBRACE Calculator — [EMBRACE_Project_20260428_work.db]

File Report Help

EMBRACE method | EMBRACE dependency method

Menu

EMBRACE method

Search Option

HFE: Input text

HEP: Input number ~ Input number

FPtp: Input number ~ Input number

FPce: Input number ~ Input number

Proc: Input text (e.g. SPTA, FRP)

Search

HFE list

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	Case2: poil...	3.82E-01	8..
	Pressure c...	1.77E-03	1.(
	Example2	3.10E-02	2..
▸	**Example...**	**0.00E+00**	**0.0**

New | Delete | Duplicate

Basic Info | FPtp | FPce

HFE Name: Example HFE

Start Step: Select Procedure | Select Step

End Step: Select Procedure | Select Step

Generate Task Breakdown

Builds primitive task rows from the selected Start → End steps (including waypoints).

Undo | Redo

Procedure Flow and Primitive Tasks

Procedure flow diagram will appear here.

Primitive task list will appear here.

Proc	Step	Important	SubStep	Content	TaskType	PEP	Perf. #	Step Sum	Step Type	PSF

Add Row | Delete Row | Duplicate Row | Select all tasks as important

Recovery Failure Probability (RFP)

Crew/Cue/Procedure Recovery

- Shift change recovery (0.0164)
- Recovery from apparent cue (0.0164)
- Recheck in stable status (0.05)
- Recovery by procedure (0.5)

STA Monitoring Recovery

- 1st attempt (22min<=Time margin<37min) (0.5)
- 2nd attempt (Time margin>=37min) (0.14)
- No credit (1)

* Tavail = 0; Treq = 0; Time margin = 0

Calculate FPce

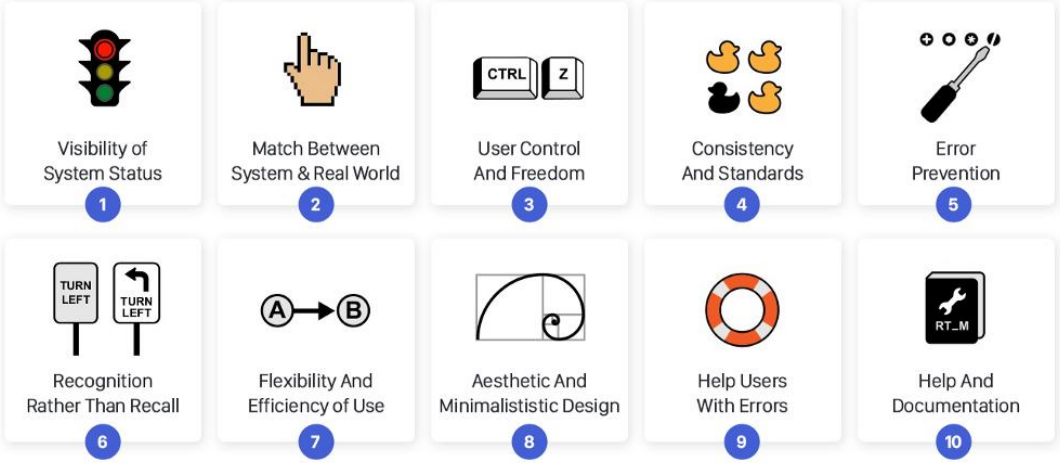
Total PEP: 0.00E+00

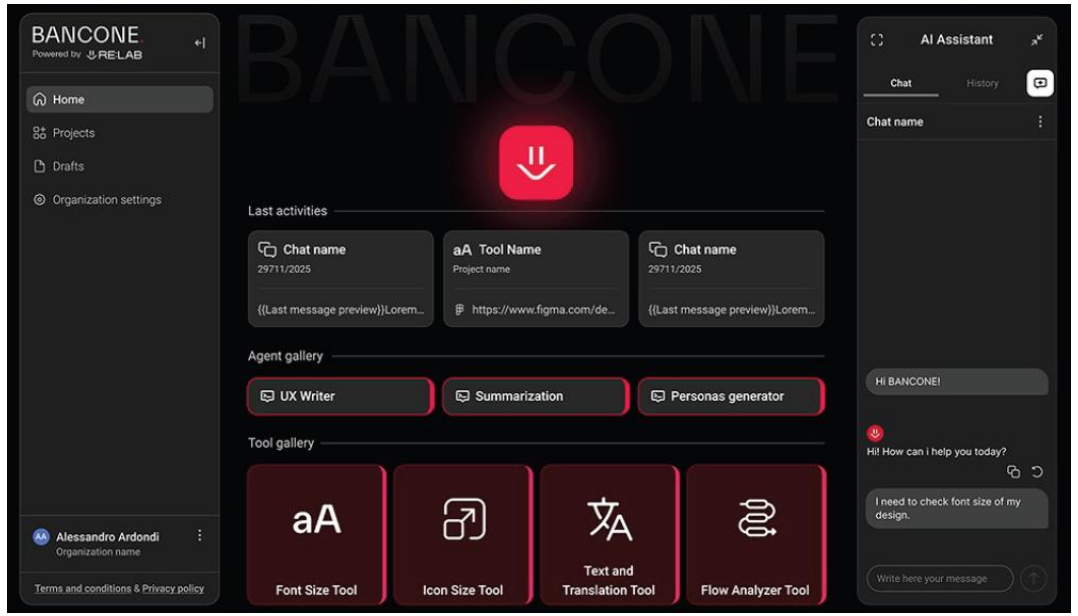
RFP: 1.00E+00

FPce: 0.00E+00

Usability Evaluation Method

- The usability of software under development was evaluated.
  - 5 experts in human-factors and human-computer interaction
    - Nielsen's 10 usability heuristics
    - Cognitive and visual risk evaluation
  - AI-assisted expert evaluation
    - BANCONE: a RAG-based AI platform to support assessing, designing, and localizing user interfaces.
    - Developed by RE:LAB: an Italian company with over 20 years of expertise in Human-Machine Interface (HMI) design and user experience





RAG: Retrieval-Augmented Generation

Usability Evaluation Process

Preparation & Definition

1. Understand the EMBRACE Method and ESS
2. Establish Evaluation Frameworks
3. Define Tasks and Scenarios for Analysis

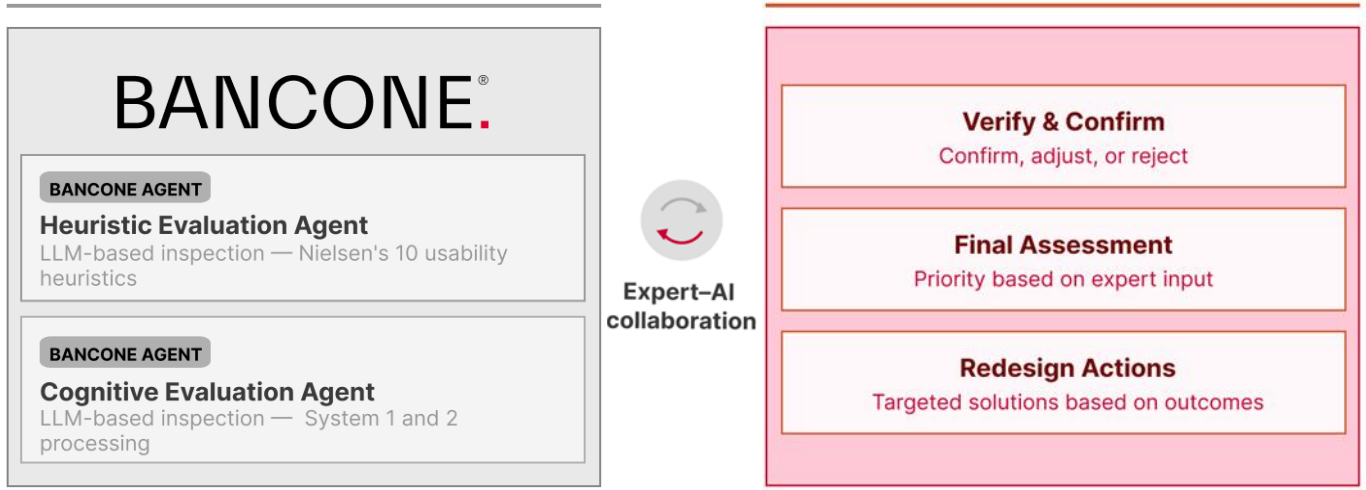
AI-Assisted Evaluation

4. Execute AI-Driven Analysis via BANCONE
5. Synthesize AI-Generated Diagnostic Outputs

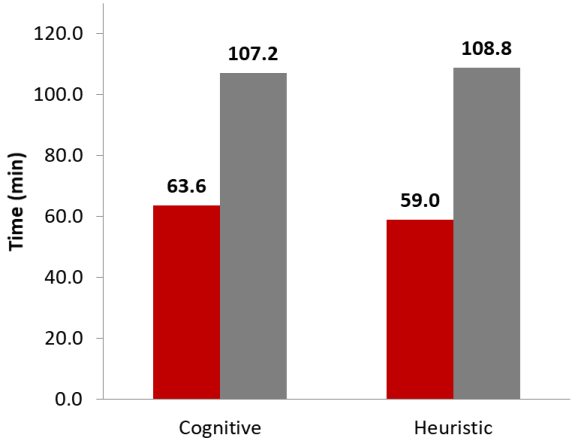
Integration & Reporting

6. Compare and Integrate AI-Driven and Expert-Driven Findings
7. Assess Usability Levels and Derive Redesign Recommendations
8. Generate the Final Usability Report

- Expert-AI collaboration for usability evaluation



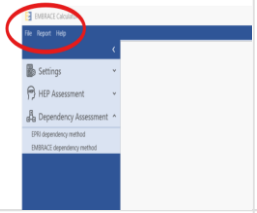
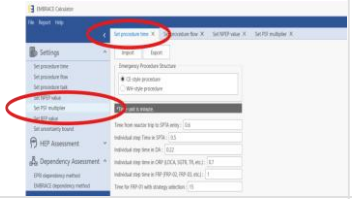
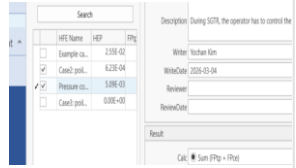
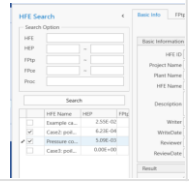
- The AI-assisted process improves the evaluation efficiency.
  - AI + expert evaluation time
  - Expert only evaluation time



Usability Evaluation Result

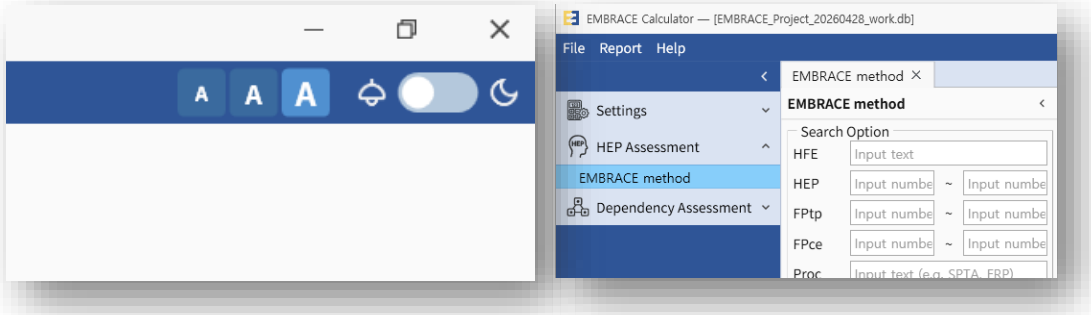
- Total Identified Issues: 81
  - Severity 4: 17 (21%)
  - Severity 3: 26 (32%)
  - Severity 2 or 1: 38 (47%)

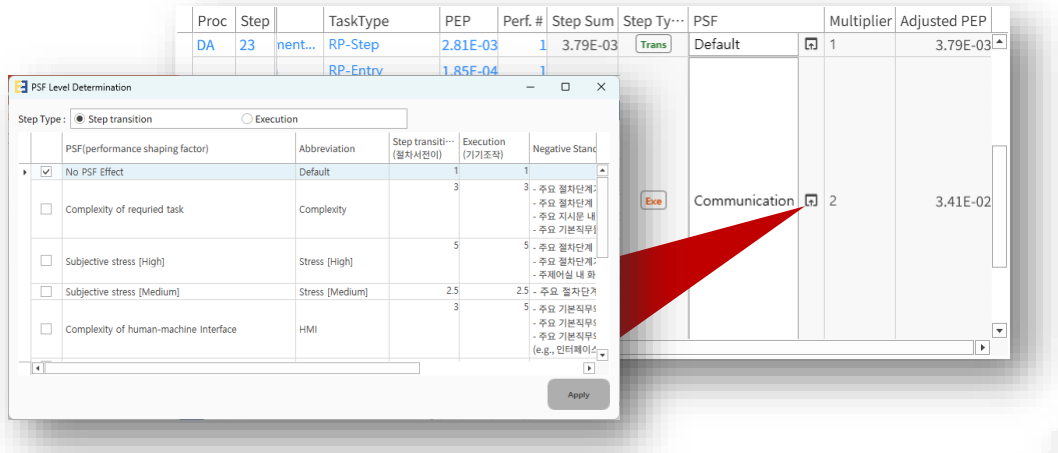
- Violated Usability Categories
  - Consistency and Standards: Overlapping menu interactions and mismatched button behaviors.
  - Aesthetic and Minimalist Design: Excessive technical abbreviations and cluttered display areas.
  - Visibility of System Status: Lack of instant feedback.
  - Error Prevention: Absence of confirmation dialogs before destructive actions.

ID	Issue Description	Severity	Violated Heuristic / Cognitive Problem Type	PICTURE EXAMPLE	Redesign Suggestion
4	Top menu items ('File', 'Report', 'Help') are very small, have insufficient color contrast, and lack visual prominence.+ Top menu items ('File', 'Report', 'Help') behave inconsistently when clicked, with differing interaction patterns and feedback	3	**Visibility of System Status + Consistency and Standards**		Increase the size of the 'File', 'Report', and 'Help' top bar items to a minimum of 14px (16px on mobile),
5	When moving among tabs, the left navigation menu highlights the previously opened tab instead of the currently active one.	2	**Visibility of System Status**		Ensure the left navigation menu always highlights the currently active tab rather than the
6	The HFE list uses checkboxes suggesting multi-selection, but only one HFE can be displayed at a time, creating a misleading interaction pattern.	3	**Consistency and Standards**		Replace checkboxes in the HFE list with a single-selection mechanism (e.g., a
7	The HFE Search panel does not allow manual resizing and resets its width when minimized/reopened or when switching tabs.	2	**Consistency and Standards**		Implement resizable panel functionality so users can manually adjust the HFE

Improvements

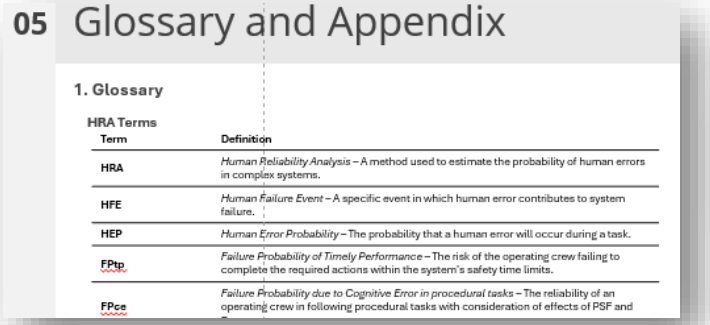
1 · Font size issues & poor menu navigation feedback
The top menu fonts are too small and cannot be resized, hindering readability. The left navigation menu lacks proper active state highlighting and high-contrast color indicators, which section is currently being operated.

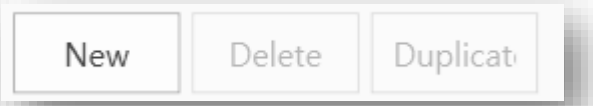




2 · Visual affordance mismatch & incorrect icon convention
The use of dropdown arrows on buttons designed to open pop-up windows creates incorrect interaction expectations for users. These dropdown symbols should be replaced with standardized pop-up or window-launching icons.

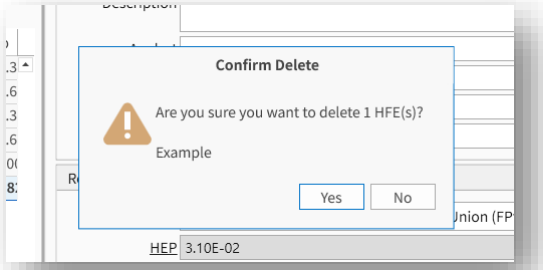
3 · Cryptic terminology & non-responsive layout
The interface relies heavily on unexplained acronyms (HFE, HEP, FPtp, PSF, RFP...) with no glossary or help. Some buttons are not visible due to the interface not adapting to screen size.

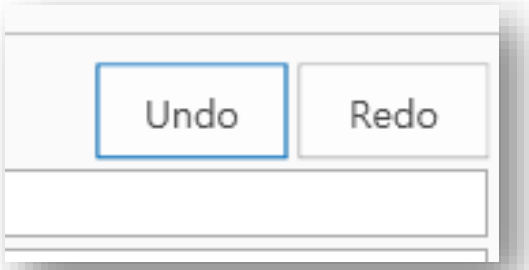


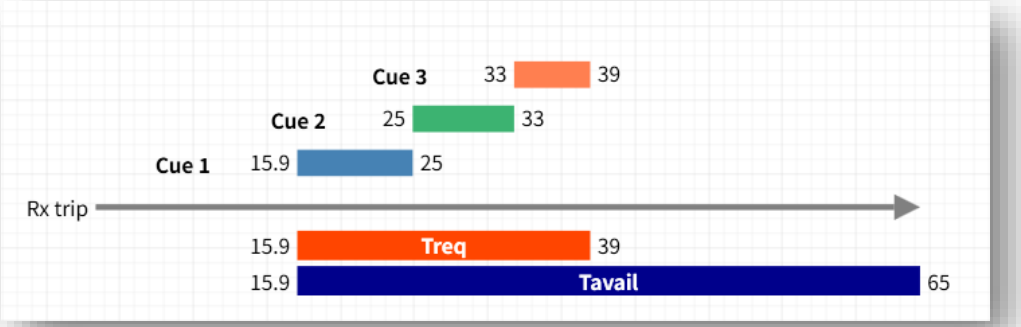


Improvements

4 · Error prevention & recovery failures
Destructive actions (delete HFE, delete row) proceed without confirmation. Undo is non-functional for critical operations. No real-time field validation — errors surface only at calculation time, making them hard to trace.

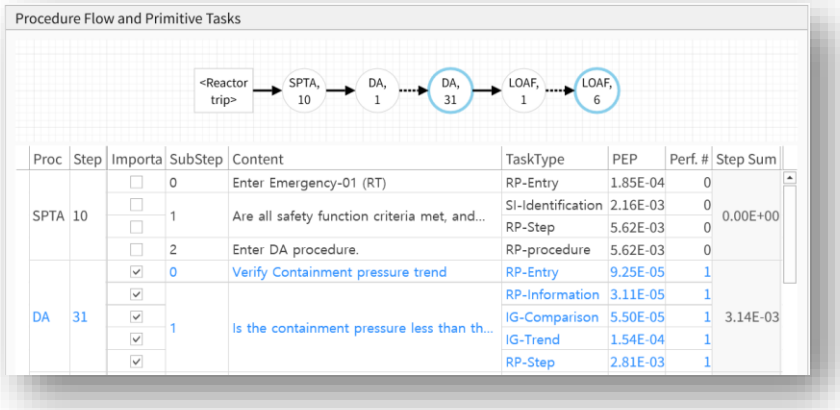






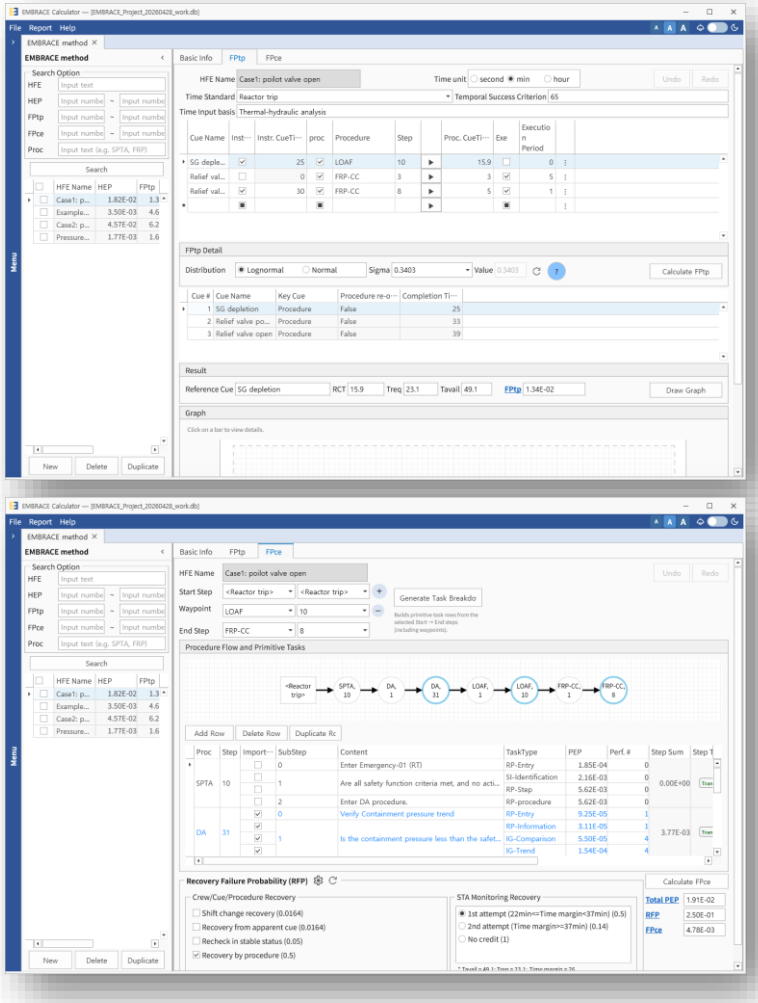
5 · Inadequate legend & visual key in timeline graph
The timeline graph generated alongside the FPtp calculation lacks proper legends for the elapsed time of each cue, "Time Required" (Treq), and "Time Available" (Tavail).

6 · Inconsistent visual encoding & color-mapping
During FPce calculation, the color of the selected critical step nodes in the procedure flowchart does not match the color highlighted in the corresponding primitive task table. This mismatch in color-coding can lead to analyst disorientation.



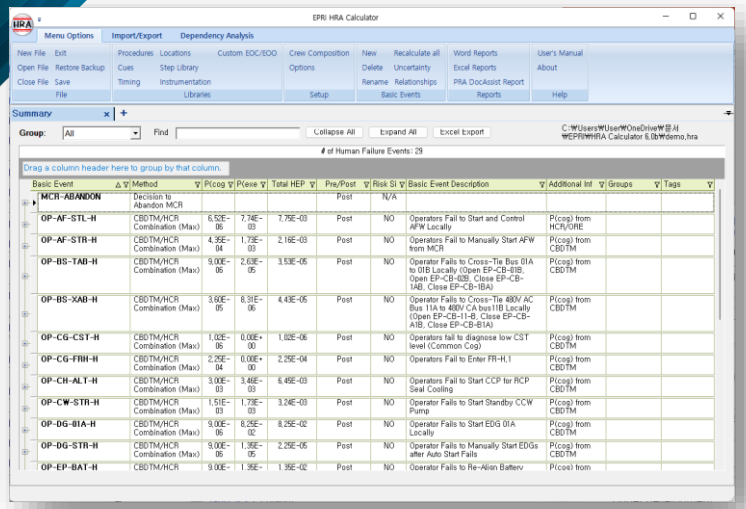
Summary and Future Work

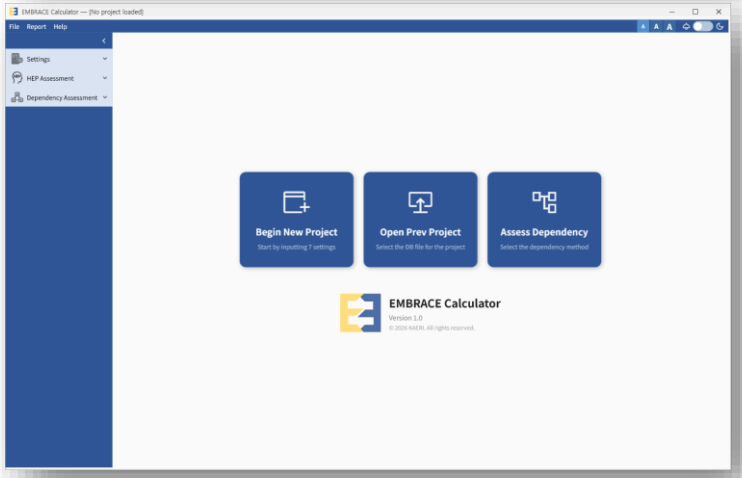
- Summary: The EMBRACE Method & ESS
  - Empirical HRA Framework: A novel, data-driven HRA method designed for empirical HEP quantification, dependency assessment, and parameter uncertainty estimation.
  - Automated Support Tool (ESS): Seamlessly links procedural and temporal data with HFEs, automatically generating dynamic visual flowcharts for analysts.
  - Hybrid Usability Validation: Conducted an expert-AI collaborative evaluation via the BANCONE platform, systematically identifying and classifying 81 usability issues to drive system redesign.



- Future work
  - Regulatory Application: The EMBRACE method and ESS will be employed in the regulatory review of APR1400 PSA.
  - SMR HRA Extension: Ongoing research is extending the methodology to Small Modular Reactors (SMRs), utilizing empirical human performance data collected from laboratory experiment campaigns.

Comparison with EPRI Calculator





Feature/Dimension	EMBRACE Support Software	EPRI HRA Calculator
Supported HRA Methods	Focused on EMBRACE method	General-purpose (ASEP, CBDT, HCR/ORE, THERP, SPAR-H)
Workflow & UI Architecture	Hierarchical lateral navigation (Sequential, workflow-oriented)	Top-menu and module-based navigation
Procedure & Task Mapping	Direct integration of procedure logic & auto-suggested PTs based on HuREX empirical data	High reliance on manual cross-referencing
Timeline Analysis	Supports temporal data comparison, time-series graphs, and multi-cue reference time Algorithm	Supports temporal data comparison and time-series graph visualizations
Parameter Uncertainty	Flexible selection of rules (THERP, SPAR-H, or EMBRACE)	Depends on the selected method
Dependency Analysis	Dual-track: EPRI decision tree-based and KAERI's multi-variable equation	EPRI decision tree-based
PRA Software Integration	Under development	Automated HFE generation via integration with external PRA (e.g., CAFTA/RiskSpectrum)
Market Status & Maturity	Under software development; focusing on user-friendliness & user familiarization	Industry standard with an established, extensive global user base (esp. North America)

Thank You

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BANCONE AI Agents

Agent Name	Category	Description	Input Type	Output Type
Create and Interact with User Persona	User Research Qualitative Analysis	Generates detailed user personas for UX/UI design and allow to have a conversation with them.	Information about demographics, user goals, behaviors (eg. from interviews, user research activities...).	A comprehensive user persona profiles based on the input data; a direct chat with the personas themselves.
Heuristics Analysis	HMI Design HMI Design Evaluation	Evaluates UX/UI designs against established heuristics (e.g. Nielsen&Norman 10 herustics).	UI designs, specifications, screenshots.	Heuristic evaluation report, improvement suggestions.
KANNY	HMI Design Evaluation	Analyzes design from a cognitive perspective, identifying strengths, weaknesses, and opportunities for improvement.	Design specifications, interface images.	Validation report, suggestions for improvements.
Cross-cultural HMI Design Recommender	HMI Design HMI Design Evaluation	Suggests and evaluate HMI design considering cultural differences.	Design specifications, interface images, target cultures.	Cutlurally-adapted HMI recommendations.
Accessibility	HMI Design Evaluation	A digital accessibility consultant that identifies usability barriers and suggests inclusive design improvements.	UI elements, websites apps displays interfaces.	Analysis report, suggestions for improvements.
Copywriting Agent	Copywriting support Marketing/Communication	Creates and optimizes interface text across platforms.	UI element details, brand guidelines.	Optimized copy, alternatives, rationale.
Text and Translation Quality	Text quality evaluation Copywriting support	Evaluates and improves text translations with respect to the context of use for accuracy and cultural fit.	Source text, translations (.xlsx, .po file...)	Quality scores based on various linguistics parameters, improvement suggestions.
SpecGuru	Specifications validation	Validate specifications documents for structure, syntax, logical consistency.	Specifications documents.	Validation report, suggestions for improvements.
TestGuru	Test case validation	Helps creating and validating test cases for product's HMI.	specifications files, already-developed test cases.	New generated test cases, test case validation report.

BANCONE Report

- Report Example
  - “Evaluate the software usability based on the attached file.”
    - Manual including screenshots of the software and descriptions of the software functions

Cognitive Issue	Impact Severity	Cognitive Principle Violated	Redesign Suggestion
Inconsistent color coding for valve states without legends forces operators to rely on memory rather than perceptual recognition	🟡 3 - Major Decision-Making Impact	Recognition vs. Recall (Memory Retrieval)	Add a persistent legend in a fixed location showing "Green = Open, Red = Closed" with example valve icons. Consider using shape coding in addition to color (triangles for open, circles for closed) to support colorblind operators.
Critical numerical values displayed in varying font sizes and colors without hierarchical organization	🟡 3 - Major Decision-Making Impact	Visual Attention & Saliency	Establish a consistent visual hierarchy: use larger, bold fonts for primary parameters (reactor power, core temp), medium fonts for secondary parameters (flow rates), and smaller fonts for tertiary information (batch numbers). Reserve red color exclusively for alarm conditions.
"MAKEUP MODE" control panel uses five unlabeled buttons below mode indicators	🟠 4 - Critical Cognitive Failure	Recognition vs. Recall (Memory Retrieval)	Add text labels directly on or immediately below each button (MAN, BOR, AUTO, ALT, DIL). Use icons that represent each mode's function. Highlight

System Usability Scale (SUS) Results

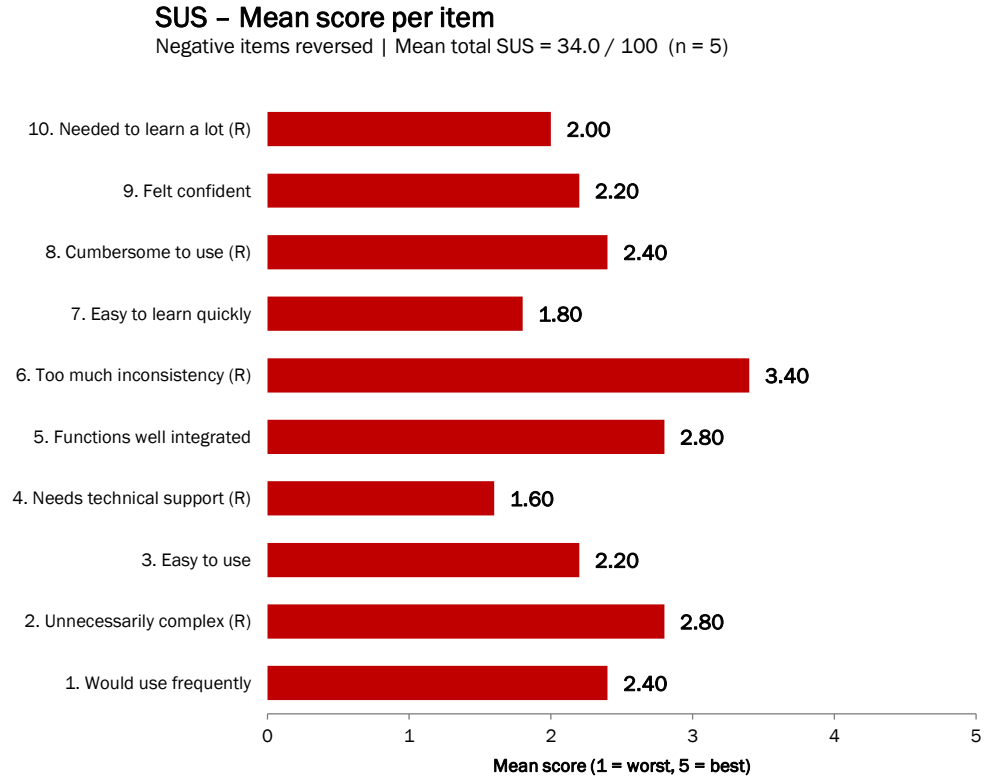
Overall Finding:

Usability score of 34/100 indicates a necessity to improve usability.

Key Findings:

- **Strengths**
  - Functions are somewhat integrated
  - Moderate willingness to use
- **Weaknesses**
  - Needs technical support (1.60)
  - Hard to learn (1.80)
  - Perceived inconsistency (3.40 – major issue)
  - Complexity too high (2.80)

- Overall, a score at this level signals that usability should be treated as a priority, and that targeted design improvements are needed before scaling or further development.



Negative items were reverse-scored. Higher values indicate better usability (1 = worst, 5 = best).