

MULTI-STATE FLIGHT DECK DISPLAY LAYOUT OPTIMIZATION UNDER FAILURE AND REVERSION CONDITIONS

Yoichi Yamai[1], Makoto Itoh[2], Marie-Pierre Pacaux-Lemoine[3]

[1]*Institute of Systems and Information Engineering, University of Tsukuba, Tsukuba Japan*
[2]*Institute of Systems and Information Engineering, Center for Artificial Intelligence Research, Tsukuba Institute of Advanced Research, University of Tsukuba, Tsukuba Japan*
[3]*LAMIH - UMR CNRS 8201, Université Polytechnique Hauts-de-France, Valenciennes, France*

Abstract

In next-generation commercial aircraft as well as retrofit programs for existing fleets, flight deck display layout design plays a critical role in pilot situation awareness and cognitive workload management and operational resilience under degraded conditions. Recent glass flight deck architectures integrate large amounts of information into digital displays, requiring layouts that ensure operational continuity not only under nominal conditions but also across degraded operational states and reversion transitions caused by display failures. At the same time, aircraft development programs face increasing pressure to shorten development cycles, highlighting the importance of front-loading human-centered design decisions in the early design phase.

In previous studies, we formulated quantitative cognitive evaluation metrics based on pilot eye movement behavior and applied integer linear programming (ILP) to optimize display layouts. However, previous optimization primarily addressed static layout design under isolated operational conditions, whereas practical flight deck design requires layouts that remain operationally feasible across multiple degraded states and preserve continuity of critical information during reversion transitions.

This study proposes a multi-state optimization framework for flight deck display layout design under nominal, single-display failure, and dual-display failure conditions. The framework integrates human-factors-oriented evaluation metrics, including pilot eye movement workload and visibility characteristics, together with continuity preservation of critical displays during degraded-state transitions. In particular, continuity of Primary Flight Displays (PFDs) and Engine Indication and Crew Alerting System (EICAS) information is explicitly prioritized to reflect practical operational requirements for resilient flight operations under degraded conditions.

Numerical experiments compare a baseline multi-state optimization formulation and a continuity-aware formulation incorporating reversion transition constraints. Results indicate that continuity-aware optimization significantly improves operational consistency during degraded-state transitions. Furthermore, the proposed formulation reduces cumulative relocation of critical displays by approximately 60% during reversion transitions while remaining computationally practical for early-stage design exploration.

The proposed framework extends conventional human-factors-oriented layout optimization toward resilience-aware flight deck design. The methodology provides a practical exact optimization approach for early-stage development of resilient flight deck display layouts for current commercial aircraft and establishes a foundation for future highly automated and reduced-crew operational concepts.

Keywords: Flight Deck Display Layout, Multi-State Optimization, Human-Centered Design, Integer Linear Programming, Degraded Operation

1. Introduction

1.1 Background

Modern commercial aircrafts are increasingly equipped with glass cockpit architectures in which integrated digital displays are used to present flight, navigation, and system information to support pilot situation awareness and decision-making. Although integrated displays can improve pilot situation awareness under nominal conditions, mismatches between display layouts and human cognitive characteristics may increase the risk of human errors, especially in highly automated operational environments [1,2].

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From a certification and operational safety perspective, display layout design must ensure not only safe nominal operation but also continuity of critical information under degraded conditions such as partial or complete display failures. Even in current two-pilot operations, inappropriate allocation or abrupt relocation of critical information under failure conditions can significantly increase cognitive workload and degrade pilot performance. Robust display layouts that explicitly consider abnormal and degraded operational states are therefore essential [3,4], and become even more critical in future concepts involving higher automation and reduced crew redundancy.

Modern glass-cockpit aircraft increasingly employ display reconfiguration functions to maintain information availability following display failures. Under such conditions, critical flight information may be relocated to alternative display areas through reversion mechanisms. Although these functions improve system availability and fault tolerance, they may also require flight crews to identify and reorient to relocated information sources during ongoing operations.

Previous research in situation awareness and visual attention has emphasized the importance of efficient information acquisition and stable allocation of attention to relevant information sources [5,6]. During routine flight operations, pilots repeatedly scan and interact with critical information sources. Based on established findings in situation awareness, visual attention, and scanning behavior, unexpected changes in information location may increase visual search effort and cognitive reorientation workload before information can be effectively utilized.

Although direct measurement of pilot cognitive workload is beyond the scope of the present study, continuity of critical display locations is treated as an engineering-level surrogate indicator of potential reorientation workload. Consequently, continuity preservation is considered an important design characteristic for both current commercial aircraft employing display reconfiguration functions and future highly automated and reduced-crew operational concepts.

1.2 Research Gap

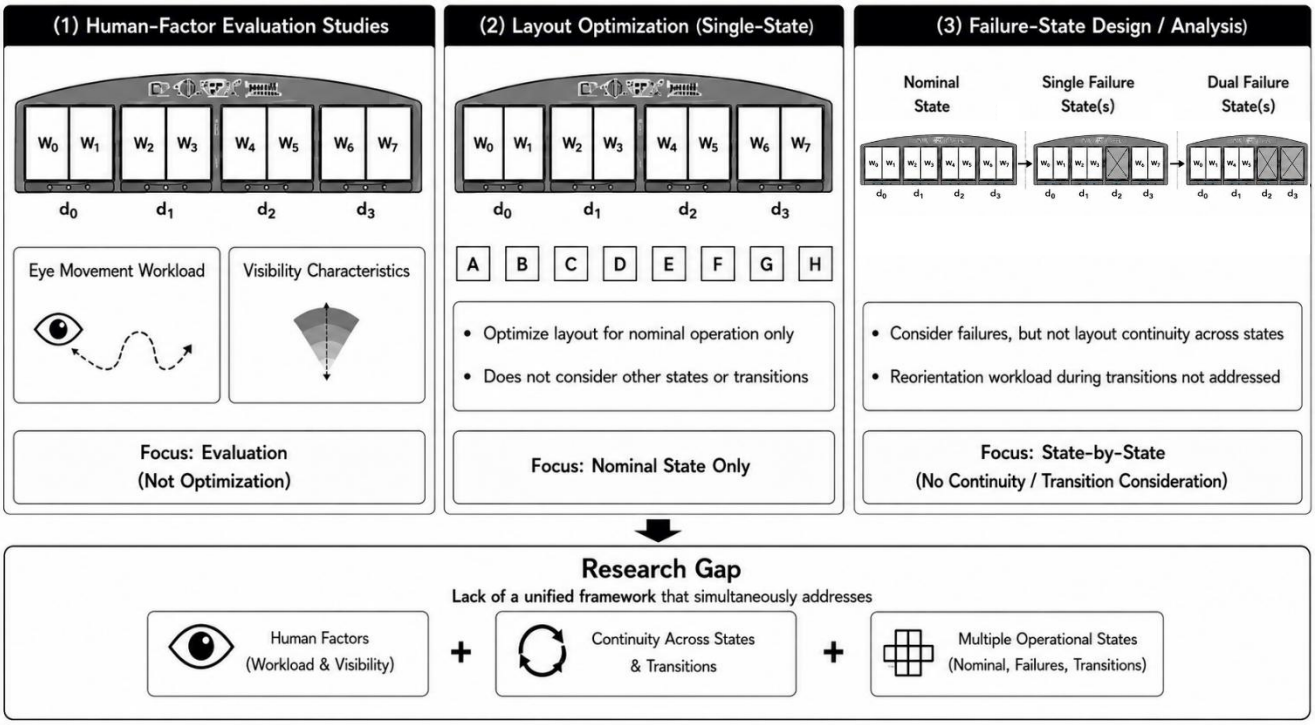
We addressed these issues through pilot evaluations using static mockups [5] and quantitative optimization using integer linear programming (ILP) based on eye-tracking-derived cognitive metrics [6]. While these studies demonstrated that human-factors-oriented optimization can effectively support flight deck display layout design, the optimization framework primarily addressed static layouts under isolated operational conditions.

However, in practical flight operations, display layouts must remain operationally feasible across multiple degraded states while preserving continuity of critical information during reversion transitions. Although modern flight deck systems employ display reconfiguration functions to maintain information availability following failures, explicit consideration of continuity preservation across operational state transitions has received limited attention in existing optimization approaches. As discussed in the previous section, continuity of critical information presentation may influence visual search effort and reorientation workload during degraded operations.

Therefore, an important gap exists between conventional static flight deck layout optimization and operationally realistic design requirements involving degraded conditions, transition continuity, and operational resilience. Addressing this gap requires a design methodology capable of simultaneously considering nominal operation, degraded operational states, and continuity of critical information presentation within a unified optimization framework.

While surrogate-assisted acceleration may remain a promising extension for larger future design spaces, the present study focuses on establishing an operationally realistic exact optimization framework for the current problem scale.

Figure 1 summarizes the positioning of the present study relative to previous research. While prior studies have addressed human-factors evaluation, static layout optimization, and failure-state analysis independently, the proposed framework explicitly incorporates continuity preservation across operational state transitions within a unified multi-state optimization formulation. This integration enables continuity-aware flight deck design aimed at supporting operational resilience under degraded conditions.



(2) Explicit degraded operational constraint modeling. Operational continuity requirements under degraded conditions are explicitly modeled, ensuring continued availability of essential flight and systems information.

(3) Critical display continuity-aware reversion optimization. A transition-aware optimization formulation is introduced that explicitly prioritizes continuity of critical displays-particularly PFD and EICAS information-during degraded-state transitions.

(4) Human-factors metric integration. Pilot eye movement workload and visibility characteristics are integrated into the optimization objective, enabling human-centered design evaluation of both nominal and degraded operational conditions.

(5) Demonstration of practical applicability for early-stage design exploration. Numerical experiments demonstrate that exact optimization remains computationally practical for operationally realistic early-stage flight deck design exploration.

The overall structure of the proposed continuity-aware multi-state optimization framework is illustrated in Figure 2. The framework integrates human-factors-oriented evaluation metrics and continuity evaluation across multiple operational states within a unified exact optimization formulation.

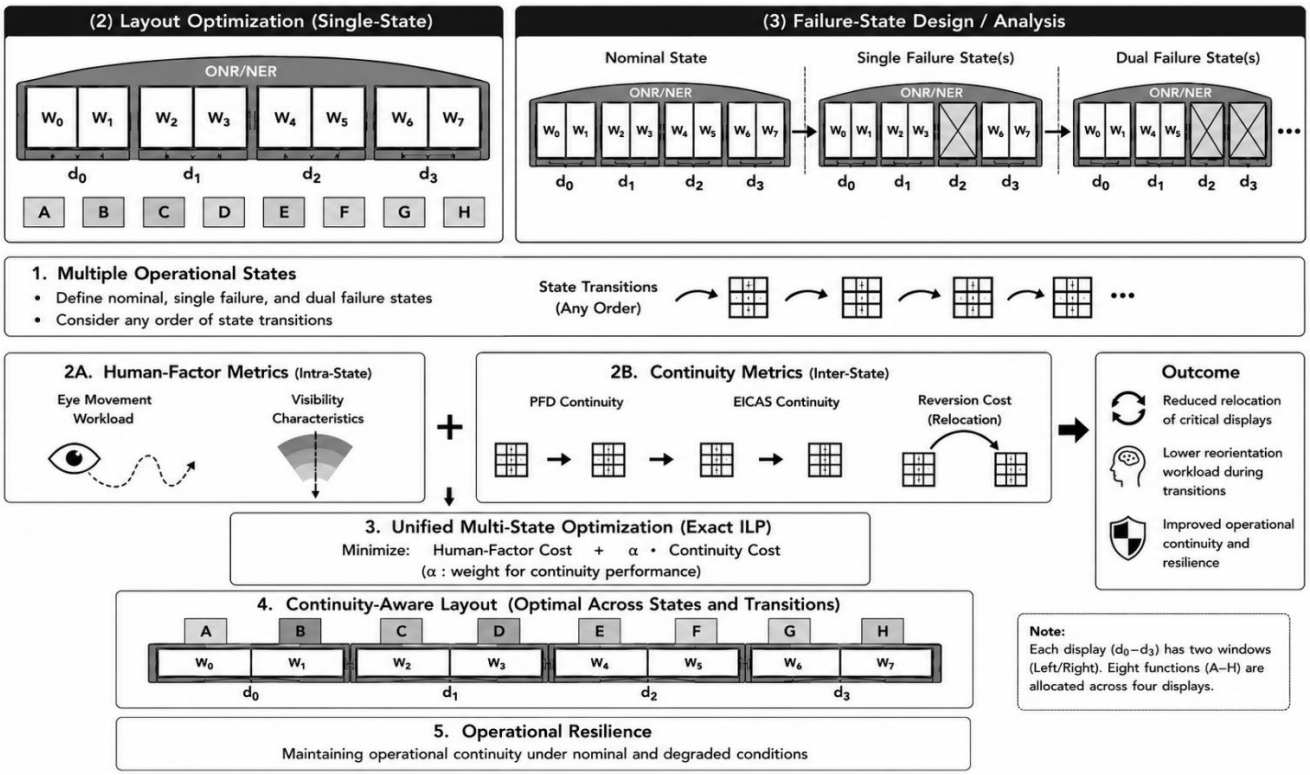


Figure 2 Continuity-Aware Multi-State Optimization Framework.

2. Related Works

2.1. Evolution of Flight Deck Display Layout Design and Emerging Challenges

Conventional instrument layouts in commercial aircraft have historically been based on standardized design concepts [10]. However, as operational concepts have become more advanced and automation levels have increased, new operational requirements that were not originally anticipated have emerged [11].

Recent advances in display enlargement and integration have expanded the range of information that can be presented on a single screen, enabling more flexible layout designs beyond traditional fixed configurations. This increased flexibility has led to a rapid expansion of the design space, particularly when considering information reallocation under display failures, degraded operational status, and changes in pilot cognitive workload. As a result, layout design approaches based on empirical rules are becoming increasingly insufficient.

2.2 Human Factors, Display Layout Design, and Optimization Approaches

Flight deck instrument layout design directly affects pilots' situation awareness and cognitive workload. Endsley's situation awareness theory provides a systematic explanation of how information presentation structures influence pilots' perception and decision-making processes [1]. In addition, major ergonomic guidelines for aircraft display design [12] qualitatively specify layout-related requirements intended to support safe and effective pilot performance.

However, these guidelines do not provide mathematical frameworks for systematically deriving optimal display layouts from large-scale design spaces under realistic operational constraints.

2.3 Optimization Approaches for Flight Deck Layout

Previous studies on display layout design in commercial aircraft have addressed evaluations of overall flight deck layouts [13], comparative analyses of Primary Flight Display (PFD) installation positions [14], and investigations into display format selection for Multi-Function Windows (MFW) [15]. While these studies provide valuable insights into specific instruments or display formats, they do not address combinatorial optimization of the overall layout involving PFD, EICAS, and MFW, nor do they consider nominal and degraded conditions, including multiple failure conditions, within a unified design framework.

Layout optimization has been extensively studied in operations research, particularly in facility layout problems [16]. However, these approaches do not explicitly address pilot cognitive behavior, degraded operational feasibility, or continuity of critical information required in flight deck design.

We demonstrated that exact integer linear programming (ILP) can be effectively applied to human-factors-oriented flight deck display layout optimization [9]. However, the prior formulation primarily addressed static layout optimization for isolated operational conditions and did not explicitly model degraded-state transitions.

2.4 Failure Management and Reversion Design

Modern electronic flight decks must maintain continued safe operation under degraded conditions, including failures of individual display units. In such conditions, reversion logic reallocates information from failed displays to surviving units. Although information availability may be preserved, abrupt relocation of critical displays can increase pilot cognitive workload and disrupt operational continuity during abnormal procedures. Conventional reversion design is typically guided by engineering design rules and expert review. The present study builds upon such domain knowledge by translating degraded-state continuity considerations into a formal optimization framework that enables systematic evaluation of alternative display layouts. As display flexibility and operational complexity increase, systematic quantitative approaches become increasingly valuable.

2.5 Positioning of This Study

The present study occupies a distinct position relative to prior work. Compared with static human factors studies, it explicitly addresses multi-state degraded operations and transition-aware reversion optimization. Compared with the prior static optimization work reported in [9], it extends the framework to jointly optimize across all operational states while preserving critical display continuity.

The distinguishing contribution is the formulation of an operationally realistic flight deck architecture optimization framework that explicitly integrates degraded operational feasibility and transition-aware continuity considerations.

Based on these limitations, the present study is differentiated from existing work by formulating the flight deck display layout problem using evaluation metrics grounded in pilot cognitive characteristics and by proposing a multi-state optimization framework that explicitly integrates degraded operational feasibility and transition-aware continuity of critical displays.

3. Problem Definition

3.1 Flight Deck Configuration

This study considers display layout configurations for both next-generation commercial aircraft and retrofit applications on existing fleets.

The representative flight deck consists of four integrated display units, each divided into two logical display windows, yielding eight assignable display regions as shown in Figure 3.

Each window can host one instrument from the instrument set:

$$I = \{\mathrm{PFD}_{\mathrm{PF}}, \mathrm{EICAS}_{\mathrm{PF}}, \mathrm{PFD}_{\mathrm{PM}}, \mathrm{EICAS}_{\mathrm{PM}}, \mathrm{MFW}_1, \mathrm{MFW}_2, \mathrm{MFW}_3, \mathrm{MFW}_4\}$$

where MFW denotes the Multi-Function Window.

The Pilot Flying (PF) is assumed seated in front of window W1, while the Pilot Monitoring (PM) is seated in front of window W6. Unlike conventional static layout studies, the present work explicitly considers both nominal and degraded operational conditions.

$$D = \{d_0, d_1, d_2, d_3\}$$
$$W = \{w_0, w_1, \ldots, w_7\}$$

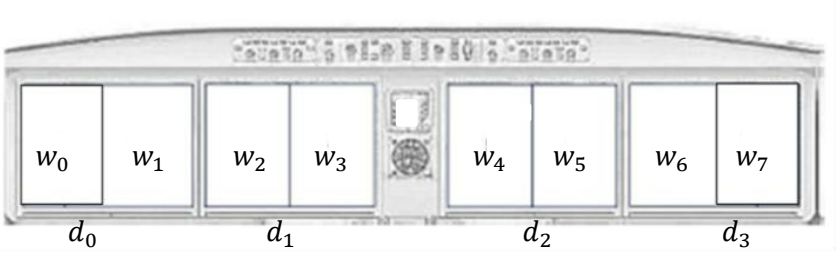


Figure 3 Display Format

3.2 Operational Scenarios

To reflect operationally realistic flight deck environments and degraded operational continuity requirements [3,4], the optimization explicitly considers nominal operation together with degraded display failure scenarios.

The scenario set is defined as:

$$S = \{s_0, s_1, \ldots, s_{10}\}$$

where $s_0 - s_{10}$correspond to the operational scenarios listed in Table 1.

Including nominal operation, four single-display failure scenarios, and six dual-display failure scenarios.

A total of eleven operational scenarios is considered.

Table 1 Summaries for the operational conditions.

Scenario	Condition	Active Windows
s_0	Normal	w_0-w_7
s_1	d_0 failure	w_2-w_7
s_2	d_1 failure	w_0-w_1, w_4-w_7
s_3	d_2 failure	w_0-w_3, w_6-w_7
s_4	d_3 failure	w_0-w_5
s_5	d_0 + d_1 failure	w_4-w_7
s_6	d_0 + d_2 failure	w_2-w_3 w_6-w_7
s_7	d_0+ d_3 failure	w_2-w_5
s_8	d_1 + d_2 failure	w_0-w_1, w_6-w_7
s_9	d_1 + d_3 failure	w_0-w_1, w_4-w_5
s_{10}	d_2 + d_3 failure	w_0-w_3

3.3 Design Objectives

The flight deck display layout problem is formulated as a discrete combinatorial design problem in which instruments are assigned to display windows under operational feasibility and degraded continuity constraints.

The design objectives are threefold as follows:

(1) The layout shall reduce pilot cognitive workload by minimizing eye movement demands during representative operational procedures.

(2) The layout should preserve favorable visibility characteristics based on pilot seating positions and human visual accessibility considerations.

(3) Continuity of critical displays should be preserved during degraded-state transitions, minimizing abrupt relocation of essential flight and systems information.

These objectives are grounded in pilot cognitive evaluation principles established in the prior work [9] and relevant flight deck human factors guidance [3].

Because the optimization jointly considers nominal operation, multiple degraded states, and transition continuity requirements, the problem becomes a structured multi-state combinatorial optimization problem.

4. Proposed Model

4.1. Overall Framework

The proposed model provides a systematic optimization framework for early-stage flight deck display layout design under nominal and degraded operational conditions.

The proposed continuity-aware multi-state optimization framework illustrated in Figure 2 is implemented through the formulation described in this section. The following subsections define the operational scenarios, human-factor evaluation metrics, optimization variables, constraints, and continuity-aware objective functions used in the numerical experiments.

(1) Representative operational scenarios are defined, including nominal operation, single-display failure conditions, and dual-display failure conditions, to reflect realistic flight deck operational environments.

(2) Human-factors-oriented evaluation metrics are formulated based on pilot cognitive characteristics. Based on the evaluation framework reported in Yamai et al.[9], flight deck layout quality is evaluated using pilot eye movement workload during representative abnormal procedures together with visibility characteristics determined by pilot seating positions.

(3) A unified multi-state exact optimization model is constructed. The formulation integrates operational feasibility constraints under degraded conditions together with continuity-aware reversion requirements for critical displays such as PFDs and EICAS displays.

(4) The optimization model is solved under two experimental configurations: a baseline multi-state formulation and a continuity-aware formulation incorporating degraded-state transition constraints.

The resulting layouts are evaluated from the three perspectives:

- operational feasibility across degraded scenarios
- continuity preservation of critical displays during reversion transitions
- computational practicality

Through this workflow, the proposed model provides a quantitative methodology for systematically exploring operationally realistic flight deck display architectures during the early design phase.

4.2. Decision Variables

The proposed optimization model is formulated as a discrete binary optimization problem.

For degraded-state continuity evaluation, the transition set is defined as:

$$\mathrm{E} \subseteq \mathrm{S} \times \mathrm{S}$$

Representing degraded operational transition pairs considered in the continuity analysis.

The primary assignment decision variable is defined as:

$$X_{siw} = \begin{cases} 1, & \text{if instrument i is assigned to window w in scenario s,} \\ 0, & \text{otherwise.} \end{cases}$$

where:

$s \in \mathrm{S}$: operational scenario,

$i \in \mathrm{I}$: instrument,

$w \in \mathrm{W}$: display window.

This variable X_{siw} represents the core flight deck layout decision across all operational states.

To represent instrument availability under degraded operational conditions, the following binary variable is introduced:

$$U_{si} = \begin{cases} 1, & if \text{ instrument i remains active in scenario s,} \\ 0, & \text{otherwise.} \end{cases}$$

To model pilot eye movement interactions between sequentially referenced instruments, auxiliary binary variables are introduced:

$$Y_{sijww'} = \begin{cases} 1, & \text{if instrument } i \text{ is assigned to } w \text{ and instrument } j \text{ to } w' \text{ in scenario } s \\ 0, & \text{otherwise.} \end{cases}$$

where: $i, j \in I, w, w' \in W$.

These variables enable linearization of pairwise eye movement workload terms.

To explicitly model degraded-state transition continuity, the following binary reversion variables are defined:

$$r_{ss'iww'} = \begin{cases} 1, & \text{if instrument } i \text{ is relocated from window } w \text{ in the display configuration} \\ & \text{of scenario } s \text{ to window } w' \text{ in the dislay configuraiton of scenario } s' \\ 0, & \text{otherwise.} \end{cases}$$

where:

$(s, s') \in \mathrm{E}$ and *E* denotes the set of degraded operational transitions.

These variables allow explicit evaluation of continuity preservation for critical displays during reversion events.

4.3. Human-Factors Evaluation Metrics

The objective function is defined based on pilot eye movement behavior and visual perception characteristics, following the human-factors evaluation framework proposed by Yamai et al. [9].

The proposed model evaluates flight deck layout quality using two cognitive evaluation components:

- pilot eye movement workload,
- visibility cost based on pilot visual accessibility.

4.3.1. Eye Movement Workload

Pilot workload is approximated using display transition distances associated with representative abnormal operational information acquisition tasks.

The eye movement workload is defined as:

$$Z_{wl} = \sum_{\mathrm{s}\in\mathrm{S}} \sum_{(\mathrm{i,j})\in\mathrm{P}} \sum_{\mathrm{w}\in\mathrm{W}} \sum_{\mathrm{w'}\in\mathrm{W}} d_{\mathrm{ww'}} y_{\mathrm{sijww'}}$$

where:

- P denotes the set of sequential instrument transitions considered in the human-factors evaluation framework,
- $d_{\mathrm{ww'}}$ denotes the Manhattan distance between display windows *w* and *w'*,
- $y_{sijww'} \in \{0,1\}$ is a binary variable indicating whether instrument i assigned to window w and instrument j assigned to window w' are sequentially referenced in scenario s.

The set of sequential instrument transitions is defined as

$P = \{(i, j)|$ instrument *j* is referenced immediately after instrument *i* in a representative operational procedure$\}$

where each ordered pair (i, j) represents a visual transition by a pilot between two instruments during task execution.

The transition set P is adopted from the prior validated evaluation framework reported in [9] and is used to estimate pilot information acquisition workload, which is treated in this study as an engineering surrogate of potential mental stress associated with display scanning behavior.

4.3.2 Visibility Cost

Visibility quality is evaluated based on the relative location of assigned displays with respect to pilot seating positions.

The visibility cost is defined as:

$$Z_{visibility} = \sum_{\mathrm{s}\in\mathrm{S}} \sum_{\mathrm{i}\in\mathrm{I}} \sum_{\mathrm{w}\in\mathrm{W}} f_i c_{\mathrm{iw}} x_{\mathrm{siw}}$$

where:

- $x_{siw} \in \{0,1\}$ is the assignment decision variable indicating whether instrument *i* is assigned to window *w* in scenario *s*,

- f_i is the gaze frequency weight representing relative instrument importance,
- c_{iw} is the visibility cost between instrument *i* assigned to window *w* and the corresponding pilot's Design Eye Point (DEP).

The gaze frequency weights f_i are adopted from the empirical human-factor evaluation framework reported in [9], reflecting the asymmetric operational roles of the PF and PM. Consistent with flight deck display visibility principles described in AC 25-11B [3], lower costs are assigned to displays located closer to the pilot's forward visual field, while higher costs are assigned to displays requiring larger visual or head movement. Specific threshold values used for numerical evaluation are described in Section 5. These cognitive evaluation metrics provide the human-factors basis for the proposed multi-state optimization model.

4.4 Reversion Continuity Model

To explicitly preserve operational continuity during degraded-state transitions, the proposed model introduces a continuity-aware reversion evaluation term. Conventional degraded flight deck design typically ensures continued availability of essential information after display failures. However, abrupt relocation of critical displays between operational states may increase pilot cognitive workload and disrupt abnormal procedure execution.

To address this issue, degraded-state transition continuity is explicitly modeled using reversion relocation variables.

The continuity penalty is defined as:

$$Z_{rev} = \sum_{(s,s')\in E} \sum_{i\in I} \sum_{w\in W} \sum_{w'\in W} P_i m_{ww'} r_{ss'iww'}$$

where:

- P_i is the continuity priority weight assigned to instrument *i,*
- $m_{ww'}$ denotes the relocation distance between display windows *w* and *w'*
- $r_{ss'iww'} \in \{0,1\}$ is the binary reversion relocation variable indicating whether instrument i is relocated from window *w* in scenario *s* to window *w'* in scenario *s'*.

The variable $r_{ss'iww'}$ identifies the correspondence of an instrument between two operational states, whereas $m_{ww'}$ quantifies the magnitude of the relocation. Therefore, the continuity penalty increases when a more critical display is relocated over a larger distance. Higher continuity penalty values correspond to larger relocations of more operationally critical displays.

Priority weights are assigned according to operational importance:

$$P(PFD) > P(EICAS) > P(MFW)$$

This reflects the need to preserve continuity of essential flight and systems information during abnormal operations. This formulation enables explicit quantitative evaluation of reversion continuity rather than relying solely on heuristic engineering judgment.4.5

4.5 Objective Function

The overall objective function combines the human-factors evaluation metrics defined in Section 4.3 with the degraded-state continuity evaluation term introduced in Section 4.4.

The optimization objective is defined as:

$$min\ Z = \alpha Z_{wl} + \beta Z_{visibility} + \gamma Z_{rev}$$

where:

- Z_{wl}: pilot eye movement workload,
- $Z_{visibility}$: visibility cost,
- Zz_{rev}: degraded-state continuity penalty.

The weighting coefficients α, β, and γ control the relative importance of human-factors performance and continuity preservation. Two optimization configurations are considered in the numerical experiments.

(1) Baseline multi-state optimization

$$\gamma = 0$$

In this configuration, optimization considers only local human-factors evaluation metrics.

(2) Continuity-aware optimization

$$\gamma > 0$$

In this configuration, degraded-state transition continuity is explicitly incorporated into the optimization objective.

This enables comparative evaluation of the trade-off between local human-factor performance and continuity preservation of critical displays.

4.6 Constraints

The optimization model is subject to assignment, operational feasibility, degraded-state continuity, and linearization constraints.

(1) Instrument Assignment Constraints

Each required instrument must be assigned to exactly one active display window in each operational scenario:

$$\sum_{w \in W} x_{siw} = u_{si} \qquad \forall s \in S, \forall i \in I,$$

where:

u_{si} indicates whether instrument i remains active in scenario s.

This ensures that all required flight deck functions are uniquely allocated under each operational condition.

(2) Window Capacity Constraints

Each display window can host at most one instrument:

$$\sum_{i \in I} x_{siw} \leq 1 \qquad \forall s \in S, \forall w \in W.$$

This prevents overlapping assignments.

(3) Failed Display Constraints

Assignments to failed display windows are prohibited:

$$x_{siw} = 0 \; \forall s \in S, \forall w \in W_{failed}(s),$$

where $W_{failed}(s)$ is the set of unavailable display windows in scenario *s*.

This enforces degraded operational feasibility.

(4) Critical Instrument Availability Constraints

To maintain continued safe operation under degraded conditions, essential flight and systems information must remain available subject to scenario feasibility. Accordingly, scenario-dependent availability constraints are imposed to preserve critical information functions while respecting reduced display capacity under failure conditions.

The availability requirement is represented as:

$$u_{si} \geq a_{si} \; \forall s \in S, \forall i \in I,$$

where $a_{si} \in \{0,1\}$ is a scenario-dependent parameter indicating whether instrument *i* is required to remain active in scenario *s*.

For single-display failure scenarios, both PFD and EICAS functions are required to remain available whenever display capacity permits. For dual-display failure scenarios, minimum critical availability is enforced so that at least one PFD function and one EICAS function remain active. This formulation avoids imposing infeasible full-information retention requirements under severe degraded conditions while preserving essential operational functionality.

(5) Eye Movement Linearization Constraints

The pairwise eye movement interaction variable $y_{sijww'}$ is linearized using standard binary product constraints:

$$y_{sijww'} \leq x_{siw},$$

$$y_{sijww'} \leq x_{sjw'},$$

$$y_{sijww'} \geq x_{siw} + x_{sjw'} - 1,$$

for all relevant indices. These constraints enable linear representation of pairwise workload terms.

(6) Reversion Continuity Constraints

To model degraded-state transitions, reversion correspondence variables $r_{ss'iww'}$ are linked to assignments in adjacent operational states:

$$r_{ss'iww'} \leq x_{siw} ,$$
$$r_{ss'iww'} \leq x_{s'iw'} ,$$
$$r_{ss'iww'} \geq x_{siw} + x_{s'iw'} - 1 ,$$

for $all\ (s, s') \in E$.

These constraints establish correspondence of instrument locations between operational states and enable continuity evaluation.

4.7 Solver Implementation

The proposed optimization model was implemented in Python using the PuLP mathematical programming framework. Exact optimization was performed using the CBC solver based on Branch-and-Bound search [13].

5. Numerical Experiments

Numerical experiments are conducted to evaluate the effectiveness of the proposed continuity-aware flight deck display layout optimization model for next-generation commercial aircraft and retrofit configurations under nominal and degraded operational conditions. The evaluation includes nominal operation, single-display failure scenarios, and dual-display failure scenarios within the unified multi-state optimization framework. To clarify the engineering impact of continuity-aware optimization, performance was compared between a baseline multi-state optimization formulation and a continuity-aware formulation incorporating degraded-state transition considerations. Representative optimized display layouts obtained under continuity-aware formulation (Case 2) are shown in Figure 4.

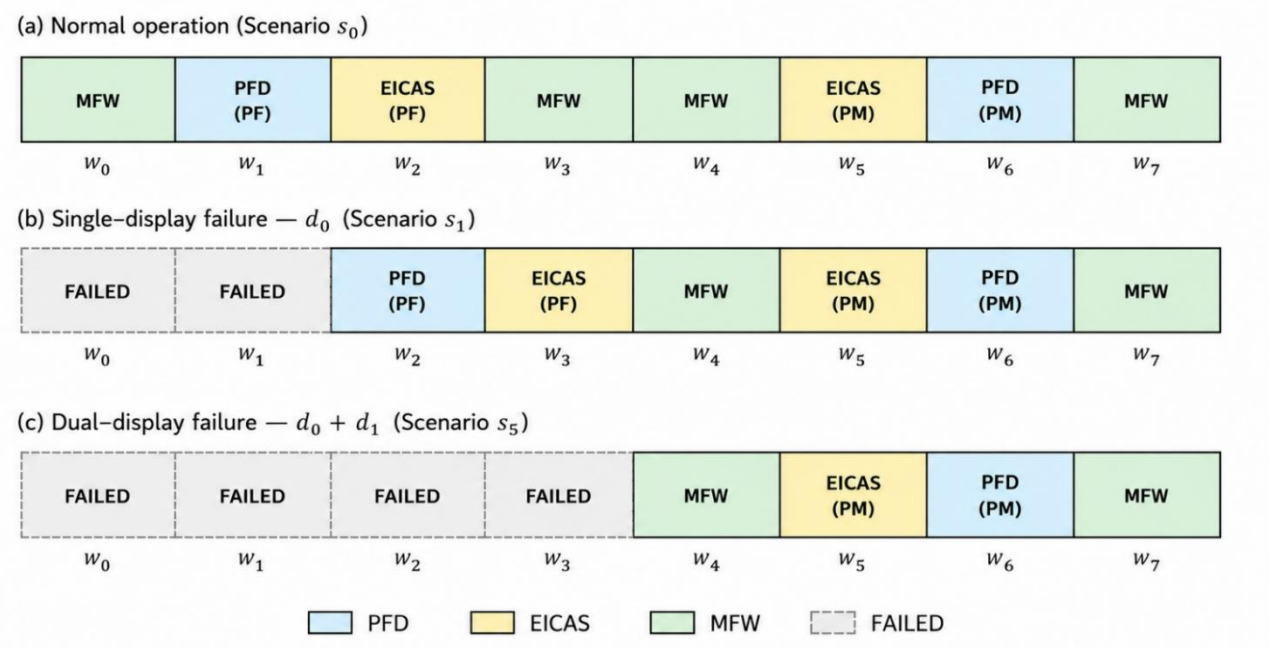


Figure 4 Representative optimized display layouts under Case 2 (continuity-aware formulation).

Evaluation metrics include:

(1) computational practicality of exact optimization,

(2) local human-factors performance in terms of eye movement workload and visibility cost, and

(3) continuity preservation of critical displays during degraded-state transitions.

Representative flight deck scenarios were defined for each operational condition to enable a consistent comparison between the baseline and continuity-aware formulations. This comparative

evaluation enables quantitative assessment of whether explicit continuity-aware optimization improves degraded operational robustness while maintaining acceptable human-factors performance and computational practicality for early-stage flight deck design. This property is particularly important in aircraft design problems, where safety, interpretability, and reproducibility are critical requirements.

5.1 Experimental Setup

Representative experimental assumptions were defined to instantiate the optimization framework for comparative evaluation. To improve operational realism, representative pilot display-reference sequences inspired by multiple non-normal operational procedures were incorporated into the evaluation, including Engine Fire, Cabin Altitude Warning / Rapid Depressurization, and Autopilot Disengage. These sequences were modeled as simplified engineering abstractions to represent typical information acquisition behavior during abnormal operations.

For the human-factors evaluation, Pilot seating positions were modeled using fixed DEP references, with the PF: aligned with window $w_1$and PM: aligned with window w_6. These reference positions were used for visibility evaluation.

The ordinal visibility penalty introduced in Section 4.3 was implemented using simplified engineering thresholds based on window-unit distance from the corresponding pilot reference position. Lower penalties were assigned to display locations closer to the pilot's field of view, while higher penalties were assigned to locations requiring greater visual or head movement. This simplified model was intended to provide a comparative measures of display accessibility during early-stage design exploration rather than a certified visual-angle assessment based on detail cockpit geometry.

All numerical experiments were executed on a standard laptop computer (Intel Core i5, 8 GB RAM) using single-threaded execution

5.2 Experimental Cases

Two optimization configurations were defined for comparative evaluation.

(1) Case 1: Baseline Multi-State Optimization

In this configuration, degraded-state continuity is not explicitly considered in the optimization objective. Accordingly, display layouts are optimized solely based on local human-factors performance within each operational scenario.

(2) Case 2: Continuity-Aware Optimization

In this configuration, degraded-state continuity is explicitly incorporated into the optimization objective. Relocation of critical displays across degraded operational transitions is penalized in order to encourage continuity preservation.

For fair comparison, both cases were evaluated using the same 11 operational scenarios defined in Table 1 and shared the same decision variables, feasibility constraints, engineering weighting parameters, and exact ILP solution framework. The only difference was the explicit inclusion of degraded-state continuity evaluation in Case 2. The comparison between Case 1 and Case 2 enables quantitative assessment of whether degraded-state continuity can be improved without materially degrading human-factors performance.

5.3 Results

The proposed continuity-aware optimization framework was evaluated from three perspectives: computational practicality, local human-factors performance, and degraded-state continuity preservation. The following subsections compare the baseline and continuity-aware formulations to clarify the engineering impact of explicitly modeling degraded-state continuity.

5.3.1 Optimization Scale and Computational Performance

To evaluate the computational impact of explicitly modeling degraded-state continuity, the optimization scale and computational performance were compared between the two experimental cases. Table 2 summarizes the optimization scale and computational performance.

Table 2. Optimization scale and computational performance comparison

Case	Optimization formulation	Solve time [s]	Optimality
Case 1	Baseline multi-state formulation	4.33	Optimal
Case 2	Continuity-aware formulation	34.14	Optimal

As expected, the continuity-aware formulation substantially increased the optimization problem size due to the introduction of degraded-state transition continuity variables and associated constraints. Compared with the baseline formulation, the continuity-aware model approximately doubled the number of binary decision variables and constraints, resulting in an approximately one-order-of-magnitude increase in solution time. Nevertheless, both formulations were solved to exact optimality within practically acceptable runtimes. These results suggest that operationally realistic degraded-state continuity requirements can be incorporated into early-stage flight deck design while maintaining the computational practicality of exact optimization and without resorting to heuristic approximation.

5.3.2 Human-Factors Performance Comparison

Beyond computational feasibility, it is necessary to examine whether introducing continuity-aware optimization affects the human-factors quality of the resulting flight deck layouts. Pilot eye movement workload and visibility cost were therefore compared between the two experimental cases.

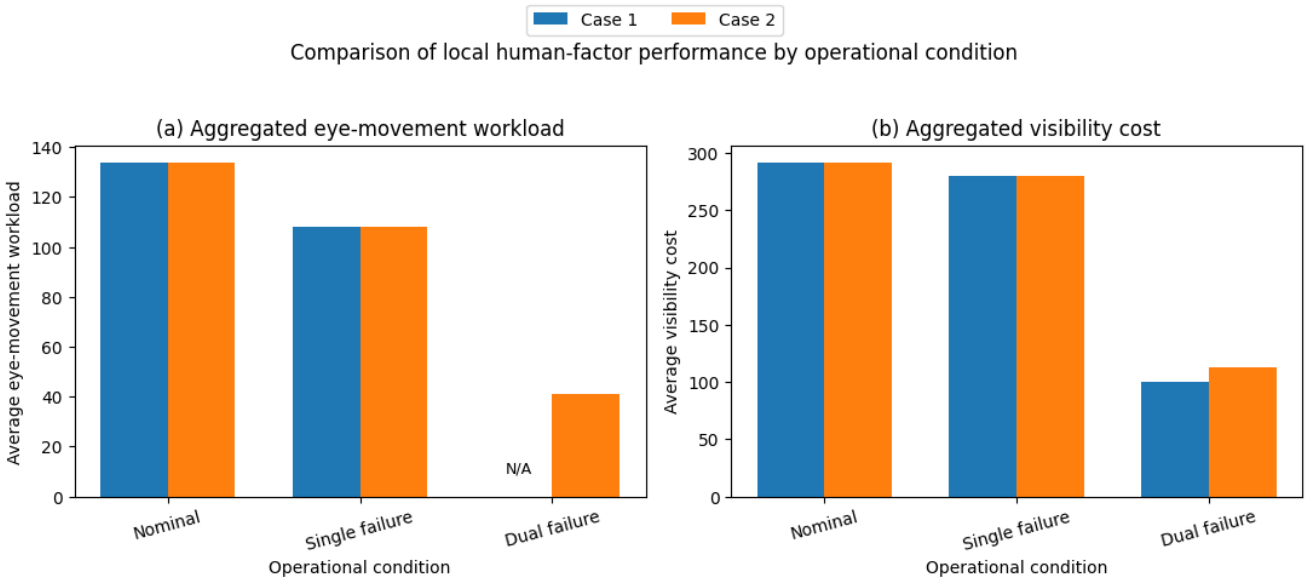


Figure 5. Summary comparison of human-factors performance across all operational scenarios

Figure 5 shows that local human-factors performance remained nearly identical between the baseline and continuity-aware formulations under nominal and single-display failure conditions. Under dual-display failure conditions, the continuity-aware formulation introduced only limited degradation in local visibility performance while preserving degraded-state continuity. The results indicate that introducing continuity-aware optimization does not substantially degrade local human-factors performance. As shown in Figure 5, aggregated eye-movement workload and visibility cost remain nearly identical to those of the baseline formulation under nominal and single-display failure conditions. Only limited differences are observed under dual-display failure conditions, where continuity-preserving display reallocations result in a modest increase in visibility cost. Overall, these findings suggest that degraded-state continuity requirements can be incorporated without materially degrading conventional human-factors performance measures across most operational scenarios. While the results indicate that continuity requirements can be incorporated without substantially affecting the evaluated human-factors metrics, the present evaluation considers human-factors performance within each operational state and therefore does not directly capture pilot cognitive effects associated with transitions between operational states. Consequently, the primary benefit of continuity-aware optimization is expected to emerge during state transitions rather than within static operational states. This aspect is examined in the following section through an explicit continuity performance analysis.

5.3.3 Reversion Continuity Comparison

The principal benefit of the proposed continuity-aware optimization is expected to appear during degraded-state transitions rather than within static operational states. To evaluate the extent to

which display continuity is preserved during such transitions, continuity performance was assessed by measuring relocation of critical displays across representative degraded operational transition pairs considered in the reversion continuity model, including transitions from nominal operation to single-display failure states and from single-display failure states to feasible dual-display failure states. Figure 6 summarizes the comparison of continuity performance between the two experimental cases. The relocation counts represent cumulative critical display relocation counts (PFD and EICAS) summed over all evaluated transition pairs.

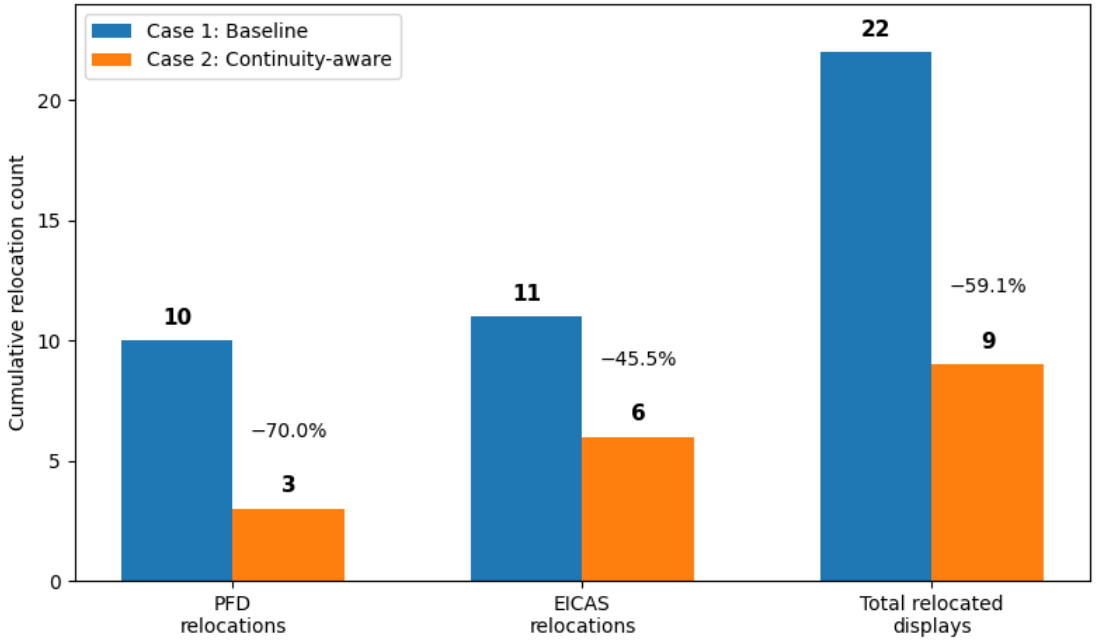


Figure 6 Reduction of critical display relocations during degraded-state transitions

The results show that the continuity-aware formulation substantially reduced relocation of critical displays during degraded operational transitions. Since abrupt relocation of critical displays may increase pilot search effort and reorientation workload during abnormal operations, reducing such relocations is expected to improve operational continuity and facilitate pilot adaptation to degraded configurations.

Importantly, these continuity improvements were achieved without materially degrading the human-factors metrics evaluated within each operational condition. Taken together, the results demonstrate that degraded-state continuity can be explicitly incorporated into flight deck layout optimization while preserving comparable workload and visibility performance. This highlights the practical value of continuity-aware optimization for supporting robust flight deck operation under degraded conditions.

5.4 Discussion

The numerical results provide several important insights regarding continuity-aware flight deck layout optimization.

(1) Explicit modeling of degraded-state continuity substantially increased optimization complexity, as expected, due to the introduction of transition-dependent decision variables and associated constraints. However, exact optimization remained computationally feasible within practically acceptable runtimes for the problem scale considered in this study. This suggests that operationally realistic degraded-state continuity requirements can be incorporated during early-stage flight deck design without resorting to heuristic approximation.

(2) Continuity-aware optimization did not produce measurable degradation in local human-factors performance. The continuity-aware formulation preserved pilot eye movement workload and visibility cost equivalent to the baseline formulation across all evaluated operational scenarios. This indicates that degraded-state continuity can be explicitly improved without sacrificing static local layout efficiency under the present problem setting.

(3) The most significant benefit appeared in degraded-state transition behavior. The continuity-

aware formulation substantially reduced relocation of critical displays, including PFD and EICAS information, across degraded operational transitions. Because abrupt relocation of critical displays may increase pilot search effort and transient cognitive disruption during abnormal operations, improved continuity is operationally desirable even when static local workload metrics remain unchanged.

(4) The scope of the situation awareness evaluation represents an important limitation of the present study. The evaluation framework is based on pilot eye movement workload and visibility characteristics, which primarily represent information acquisition processes and are therefore closely related to Level 1 Situation Awareness (perception). Higher-level cognitive processes, including comprehension of operational situations (Level 2 SA) and projection of future system states (Level 3 SA), are not explicitly modeled in the present formulation. Although efficient information acquisition is an important prerequisite for higher levels of situation awareness, improvements in Level 1 SA do not necessarily guarantee improvements in decision-making performance or operational effectiveness. Therefore, the continuity benefits demonstrated in this study should be interpreted within the scope of a Level 1 SA-oriented evaluation framework. Future research should investigate the relationship between continuity-aware display layouts and higher-level situation awareness through pilot-in-the-loop experiments and cognitive evaluations.

Based on all above, these findings suggest that continuity-aware optimization provides a practically useful extension to conventional static flight deck layout optimization by explicitly addressing operational transition robustness. However, the present conclusions should be interpreted within the scope of the Level 1 Situation Awareness-oriented evaluation framework adopted in this study.

6. Conclusion

This study proposed a continuity-aware multi-state exact optimization framework for flight deck display layout design under nominal and degraded operational conditions. The results demonstrate that degraded-state continuity can be explicitly incorporated into display layout optimization while maintaining comparable human-factors performance within individual operational states. The analysis further indicates that the principal benefit of continuity-aware optimization emerges during transitions between operational states rather than within static operational configurations. By reducing relocation of critical displays across degraded-state transitions, the proposed framework improves display continuity while preserving comparable workload and visibility performance. These findings suggest that continuity preservation can be systematically addressed during early-stage flight deck design rather than relying solely on heuristic engineering judgment.

These findings also demonstrate the feasibility of quantitatively incorporating degraded-state continuity into early-stage flight deck layout design and provide a foundation for future studies addressing pilot cognitive effects during operational-state transitions. Beyond the numerical improvements observed in the experiments, the principal contribution of this study is the introduction of a continuity-aware design methodology that explicitly incorporates degraded-state transitions into flight deck layout optimization. The proposed framework extends conventional static human-factors-oriented optimization toward resilience-oriented flight deck design by addressing operational continuity across multiple degraded operational states within a unified optimization formulation.

While these findings are encouraging, several limitations of the present study should be acknowledged. First, human-factors evaluation focused on static intra-state workload and visibility, and did not explicitly model transient pilot cognitive behavior during degraded-state transitions, such as search effort or reorientation workload during display reconfiguration. Second, the numerical evaluation employed simplified engineering assumptions regarding display geometry and visibility thresholds for comparative early-stage engineering evaluation.

Addressing these limitations will be an important direction for future research. Future work will extend the framework by incorporating dynamic transition-phase cognitive workload models, more physically realistic flight deck geometries, and broader operational scenarios, including future reduced-crew and highly automated flight deck concepts.

Although exact optimization remained computationally practical for the problem scale considered in this study, larger design spaces involving finer display discretization, expanded failure scenarios, or

increased operational complexity may significantly increase computational burden. In such cases, AI surrogate-assisted acceleration may provide a practical extension for improving scalability when combined with exact optimization frameworks.

Overall, the proposed framework provides a practical methodology for incorporating degraded-state continuity into early-stage flight deck display layout design. The study represents an initial step toward continuity-aware and resilience-oriented flight deck design methodology capable of supporting operational continuity under both nominal and degraded conditions.

Furthermore, continuity preservation may contribute to more predictable human-system interaction during degraded-state transitions. This perspective is consistent with human-centric automation principles that emphasize understandable and supportive automation behavior [16]. Such characteristics may provide a basis for future investigations of human-automation cooperation [17] and, more broadly, resilience-oriented human-AI cooperation in future adaptive flight deck systems [18].

Acknowledgment

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