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Translating Malaysia's Vision into Action with PERT, PDM and S-Curve Framework for Low-Emission Aircraft

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ABSTRACT

Malaysia is accelerating its ambition to lead in low-emission aviation, creating demand for structured planning in aircraft development. This research aims to strengthen early-stage aircraft development strategies in Malaysia by addressing planning weaknesses that often result in delays, cost overruns and weak policy alignment. The study identifies a critical gap where conventional Gantt-based approaches fail to manage high uncertainty in hybrid aircraft development. Such tools typically overlook interdependencies, slack visibility and risk forecasting, leaving project execution vulnerable. To fill this gap, the study proposes a milestone-driven framework integrating three established techniques which are Program Evaluation and Review Technique (PERT) for probabilistic time estimation, Precedence Diagram Method (PDM) for logical task mapping and dependency control and S-Curve analysis for tracking cumulative progress. A simulated hybrid aircraft development timeline was used to test the model's resilience under real-world deviations. Result demonstrates clear identification of critical paths, effective buffer allocation and proactive deviation management. Compared to static timelines, the integrated model enables dynamic scenario planning, resources flexibility and early risk detection ensuring continuity in iterative development process. The framework is structured around four milestones namely study, design, construction and commercialization. Each embedding risk evaluation and adaptive planning. In conclusion, the framework provides aerospace leaders with disciplined, adaptive tools to manage uncertainty while aligning with the Malaysia Aerospace Industry Blueprint 2030 and national decarbonization goals. Future validation with real project data, certification processes and supply chain integration is recommended to enhance scalability and strengthen Malaysia's competitiveness in hybrid aviation.

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1. Introduction

Malaysia aims to lead in green aviation however, no blueprint can deliver results without a plan that survives real world turbulence. The Malaysia Aerospace Industry Blueprint 2030 sets ambitious targets of RM55.2 billion in revenue and 32,000 high-skilled jobs by 2030 [1]. At the same time, the Aviation Decarbonisation Blueprint 2024 (ADB 2024) intensifies pressure by committing the country to net-zero emissions by 2050, with specific reductions of 18% from technological innovation and 46% through Sustainable Aviation Fuel (SAF) adoption [2]. These dual policy frameworks demonstrate vision. However, without execution discipline, they being reduced to mere aspirations.

Globally, the aerospace sector is undergoing a rapid transformation toward low-emission technologies. Hybrid-electric demonstrator programs such as VoltAero's Cassio 1 and Ampaire's Electric EEL have progressed from conceptual designs to validated endurance flights, reinforcing the feasibility of sustainable aviation operations [3],[4]. As Pullen [5] observes, electric aviation is 'no longer a distant promise, it's an advancing reality,' with record-setting demonstration flights accelerating global adoption pathway [5]. These achievements not only signal momentum, they also highlight the operational proof-of-concept that Malaysia must eventually benchmark against. Domestically, Malaysia has responded through HM Aerospace's agreement to acquire 15 VoltAero Cassio 330 hybrid-electric aircraft for pilot training [6]. Keefer and Verdini [23] introduced simplified, easy-to-use approximations for estimating the mean and variance of PERT activity times. Their methods, which require only three-point estimates and utilize more reliable probabilistic data, were shown to provide significantly improved accuracy in predicting project completion times, particularly in networks involving multiple critical paths. Such improvements are especially relevant in aviation development, where uncertainty and skewed activity durations challenge conventional PERT assumptions.

Despite incremental progress, execution challenges remain. The new Industrial Master Plan 2030 (NIMP 2030) highlights fragmented governance and limited standardisation in Malaysia's aerospace sector [7]. From a methodological perspective, conventional planning tools such as static Gantt charts have long been criticised for their inability to capture uncertainty, risk propagation and interdependency complexity. Bigelow [24] noted six decades ago that project planning research 'was rapidly outgrowing linear scheduling' and required more probabilistic approaches to survive high-risk environments [24]. This warning still echoes today in aviation projects, where shifting regulations, fragile supply chains and iterative prototypes demand more adaptive models than those inherited from construction-oriented planning.

Academic evidence supports the view that integrated scheduling frameworks are well suited to aerospace innovation. For example, Srinivasan *et al.,* [25] in their case study at Warner Robins Air Logistics Centre demonstrated that structured dependency analysis, essentially a Precedence Diagram Method (PDM) applied to depot-level aircraft maintenance, enabled faster overhaul cycles by eliminating 'hidden bottlenecks across interdependent subsystems' [25]. Such findings affirm that PDM is not just a theoretical exercise, it's a proven tool in aviation environments where component-level sequencing governs overall delivery timelines.

In parallel, S-Curve modelling has been widely applied as a performance monitoring tool in complex engineering programmes. Konor and Szostak [26] find the S-Curve can be interpreted as the 'heartbeat' of project monitoring, exposing early deviations and compelling leadership attention long before catastrophic delays manifest. This analogy resonates strongly in aerospace projects, where schedule drift during prototyping can cascade into certification failure or cost blowouts if not detected early. Their work supports the argument that S-Curve analysis, when combined with Earned

Duration Management (EDM), provides both visual clarity and decision triggers in turbulent development conditions.

At present, Malaysia's hybrid aircraft ambitions risk under-delivery not because of lack vision. Rather, the challenge lies in execution frameworks that are not yet adequately resilient to uncertainty. While the national blueprints are forward-looking, their successful execution will depend on moving beyond conventional planning tools, which provide only partial visibility in uncertain environments. The gap lies in the absence of a structured, scenario-resilient model that unifies PERT, PDM and S-Curve into a single integrated scheduling framework tailored for Malaysia's low-emission aviation development.

This study addresses a critical operational gap in Malaysia's low-emission aviation ambitions by introducing an integrated scheduling framework that combines PERT, PDM and S-Curve tracking into a unified toolset. The framework is designed to provide accurate timeline estimation, logical task mapping and deviation tracking with built-in buffer logic, enabling teams to anticipate and mitigate disruptions proactively. The objective of this study is to evaluate the practicality and resilience of the proposed framework through a simulated hybrid aircraft development timeline, testing its ability to withstand real-world deviations in Malaysia's high-uncertainty aviation development environment.

2. Methodology

This study does not use a one-size-fits-all project plan. It is designed for the messy world of hybrid aircraft development in Malaysia where regulatory updates can arrive mid-project, suppliers occasionally operate on their own timeline and prototype often choose the least convenient moment to reveal design flows. The framework is designed with built-in flexibility, embedding probabilistic buffers and dependency mapping to acknowledge that innovation seldom follows a straight line. Three tools were selected for their practical value rather than academic neatness:

PERT estimates task durations by considering the best case, the most likely and the worst case. In practice, it helps planners see beyond the "optimistic calendar" that too often guides aerospace projects.

PDM provides a clear network of task relationships, exposing critical paths and float before they cause hidden bottlenecks. It is essentially the logic map that keeps interdependent tasks from becoming a scheduling trap.

S-Curve analysis tracks cumulative progress against the plan, serving as the project's pulse check. When the curve deviates, it signals the need for corrective action long before budget or timelines collapse.

The proposed framework adopts a milestone-based structure, where each phase incorporates dedicated tools to facilitate iterative development, buffer planning and scenario analysis. This multi-tool integration approach mirrors the architectural strategy presented by Lytvyn *et al.*, [8] who describe an aviation aircraft planning system designed to streamline flight plan generation, automates data dissemination and manages scenarios in highly regulated and uncertain airspace. Their work reinforces the validity of using hybrid scheduling frameworks in aerospace innovation, particularly the importance of embedding logic control and risk visibility within each stage of complex project planning.

2.1 PERT-Based Scheduling

PERT is used to estimate how long a task might take when there is no guarantee things will go exactly to plan which is almost always. PERT scheduling offers a probabilistic method for estimating task durations under uncertainty. It uses three time estimates which are:

i. Optimistic (O), if everything goes right
ii. Most Likely (M), the realistic scenario
iii. Pessimistic (P), when Murphy's Law hits

Then the expected time TE is calculated with

$$TE = \frac{(O+4M+P)}{6} \quad (1)$$

where O = Optimistic
M = Most Likely
P = Pessimistic

This method enhances the forecasting of realistic task durations and supports the mitigation of unplanned delays. In the context of aerospace manufacturing, Ghozy [10] demonstrates how PERT, combined with crashing strategies, enables timeline optimization during aircraft assembly, offering a structured mechanism to handle resources-driven adjustments. Atli and Kahraman [9] through the application of fuzzy critical path analysis in aircraft maintenance, further reinforced the need for time estimation models that accommodate uncertainty. Complementing these, Figuero-Garcia *et al*., [11] introduces an interval type-2 fuzzy PERT approach, expanding conventional models to capture expert disagreement and probabilistic uncertainty. Collectively, these contributions affirm that PERT-based models whether classy, fuzzy or hybrid are well-suited for high risk, high variation environments such as hybrid aircraft development, where logic-driven scheduling is crucial for anticipating deviation and sustaining project control.

Variance and standard deviation are used to assign buffers:

$$\sigma^{2} = \left[\frac{(\boldsymbol{P} - \boldsymbol{O})}{\boldsymbol{6}}\right]^{\boldsymbol{2}} \quad (2)$$

In complex aerospace projects, tasks with high uncertainty such as proof-of-concept development or compliance reviews require contingency driven scheduling. Ghozy [10] illustrates how combining PERT with crashing enables planners to insert time buffers and reinforce schedule confidence, particularly in aircraft manufacturing timelines. Similarly, Figuero-Garcia *et al*., [11] demonstrates how fuzzy extension of PERT helps quantify uncertainty ranges and reduce planning guesswork. These methods offer planners a data-driven approach to timeline forecasting, especially when innovation cycles outpace conventional scheduling templates.

2.2 Precedence Diagram Method (PDM)

PDM provides visual clarity by mapping logical relationships between tasks. Relationships include Finish-to-Start (FS), Start-to-Start (SS), Finish-to-Finish (FF) and Start-to-Finish (SF) through activity-on-node diagrams. Sandora, Novitasari and Lestari [12] explain that the PDM constructs a network of project activities through logical relationships such as Finish-to-Start, Start-to-Start, Finish-to-

Finish and Start-to-Finish. This approach helps project planners determine the sequence of activities, identify the critical path and calculate float times to optimise the project schedule. As shown by Qi *et al*., [13] incorporating precedence constraints in aircraft production scheduling supports structured sequencing of tasks, enabling more effective resources allocation and coordinated dependency management across distributed manufacturing stages. While their optimization model is designed for production setting, the underlying logic parallels critical path identification in conventional project scheduling, ensuring that resources planning remains aligned with task dependencies. Similar principles have been demonstrated in large scale construction projects where resource limitations and complex task sequencing must be balanced. Ramadhona, Kurniawan and Tistogondo [14] show that PDM enables planners to pinpoint the critical path, calculate float and adjust activity schedules to maintain overall timeline. That approach is equally valuable in low-emission aircraft development where prototype development, subsystem integration and certification milestones demand precise coordination under constrained resources. The TE values from PERT are embedded into PDM to:

Identify the critical path
Calculate slack time
Plan parallel or dependent tasks

This is consistent with PMI's scheduling standard and the PMBOK treatment of three-point estimating feeding schedule network analysis [15], [16]. For example, the 'simulation testing' (SS) activity can proceed in parallel with 'design finalisation,' while 'certification submission' (FS) only begins after successful 'system validation'. As outlined in the PMBOK® Guide and PMI's Practice Standard for Scheduling, such logical relationships are core to the PDM, enabling planners to determine the critical path, calculate float and optimise the sequencing of dependent or parallel tasks to improve schedule flexibility and resilience [15], [17].

This method enhances logical task sequencing in aviation development, where simultaneous R&D, regulatory updates and supply coordination occur. In hybrid or novel systems, where 'what-if' planning matters, PDM allows planners to simulate impacts before real work begins. A similar approach is demonstrated by Qi *et al.* [13] in civil aircraft production scheduling, where precedence constraints and resources limitation are integrated into a genetic algorithm (GA)-based optimisation framework to evaluate alternative task sequences before execution, mirroring the flexibility and dependency management required in complex hybrid aircraft R&D environments. PERT time estimates are inserted into the network, enabling proactive bottleneck management. PDM remains a staple in aviation planning and is formally recognised as a best-practice in schedule logic modelling by PMI's PMBOK® Guide [15].

2.3 S-Curve Analysis

S-Curve modelling visualises cumulative progress over time, ideal for identifying deviations from planned efforts. It involves:

i. Baseline S-Curve from PERT/PDM estimates
ii. Actual progress line plotted over time
iii. Deviations triggering leadership response (e.g. resource reallocation or rescheduling)

S-Curve analysis is applied in this project to monitor cumulative effort or cost over time and detect early deviations from the baseline. In aerospace development projects, this is particularly important as budget drift or schedule overruns can arise from iterative prototyping cycles. As noted by Konor and Szostak [18], cumulative cost curves and S-Curves are widely used as a visual control method in large-scale engineering projects, enabling planners to identify early warning signs of potential deviations [18]. In complex aerospace programmes such as deviations from the planned S-Curve trajectories can serve as critical triggers for corrective action, governance reviews or scope adjustments [18].

2.4 Governance Alignment and Adaptive Logic

The strategic milestone planning model aligns with Malaysia's innovation cluster philosophy outlined in MAIB 2030. The Plan–Do–Check–Act (PDCA) cycle is adopted to embed iteration logic between milestones, ensuring that feedback from previous outputs informs subsequent planning.

For instance, after simulation feedback, the team can pivot design priorities before committing to build. This adaptive iteration makes the framework suitable for high risk, high uncertainty innovation where agility is critical.

3. Results

3.1 Strategic Planning Framework

To translate the methodology into action, this innovation journey is structured into four high level milestone clusters that capture the natural progression of aviation project planning. Table 1 presents a strategic planning framework, a structured roadmap guiding the development of a low-emission hybrid aircraft.

The study milestone begins with a comprehensive feasibility assessment or study that examines the technical viability of the proposed low-emission aircraft, its operational suitability within Malaysia's aviation ecosystem and its alignment with prevailing policy framework. This is followed by a market survey designed to map the competitive landscape, evaluate supply chain capability and establish cost benchmarks for both local and international contexts. End user requirements will be gathered through structured interviews, stakeholder workshops and operational needs analysis in effort to reflect the real-world usage expectation in the development trajectory. Parallel to these activities, the project team conducts an estimated financial requirement scoping exercise, capturing both capital expenditure and operational expenditure projection as well as identifying potential funding sources. In addition, aviation legal and regulatory compliance is also considered. To support proactive risk management, a preliminary risk register is initiated at this stage to capture early uncertainties and outline mitigation pathways before design commitments are locked in.

In summary, the framework reflects established practices in project integration, milestone design and progress control at the planning stage. Each milestone reflects readiness-based progression aligned with technical development, regulatory timing and resource availability. In other words, the milestone is designed to allow for risk review and task realignment before moving forward.

Table 1
Four milestones to structure strategic planning framework

Milestone	Key Activities	Tools
Study	Feasibility study Market survey End user's requirements Financial requirement Authority requirement Preliminary risk register	PERT, PDM
Design	Concept finalization Digital modelling Proof-of-concept readiness	PDM, S-Curve
Construction	Prototyping System integration and testing Business modelling Progress and risk tracking, monitoring and mitigation	PERT buffers, S-Curve tracking
Commercialization	Business Certification Licensing Market entry	Final PERT, governance review

3.2 PERT Simulation and Network Modelling

The practical utility of the framework, a simulated project schedule was constructed using PDM integrated with PERT time estimates. PERT allows each task to be planned with statistical awareness with no guessing, just calculated buffers. Seven key tasks were selected for this paper with each assigned three duration estimates Optimistic (O), Most Likely (M) and Pessimistic (P). These were used to calculate the Expected Time TE and standard deviation (σ) for each activity using the following Eq. (1) and (2).

3.2.1 Task Estimation and Calculation

Seven activities were considered from 'Project Initiation' to 'Ground Testing' for this paper simulation. Table 2 presents the calculated TE and σ values for each task. For instance, 'Prototype Construction' yielded a TE of 6.50 months, reflecting its inherent complexity and integration risks. 'Component Procurement' displayed a lower TE and significant float margin. This is primarily due to the nature of the items involved, mostly off-the-shelf standard components requiring minimal customisation or logistical coordination. Consequently, this task exhibits low schedule sensitivity and offers flexibility in sequencing.

Table 2
Task Table with O, M, P, TE and Standard Deviation Values

Task	Description	*O*	*M*	*P*	TE	σ	Predecessor
A	Project Initiation	2	4	8	4.33	1.00	—
B	System Architect Modelling	3	5	9	5.17	1.00	A
C	Prototype Design	4	6	10	6.00	1.00	B
D	Component Procurement	3	4	7	4.33	0.67	A
E	Prototype Construction	5	6	11	6.50	1.00	C, D
F	Ground Testing	4	5	9	5.33	0.83	E

3.2.2 PDM Network Mapping and Critical Path

The task dependencies were then plotted in a node-based network with PDM (see Figure 1). Task A (Project Initiation) starts the schedule. Task B (System Architect Modelling) depends on A. Task C (Prototype Design) follows B, while Task D (Component Procurement) can occur in parallel with C after A. Tasks E (Prototype Construction) and F (Ground Testing) depend on the completion of C and D, and E respectively. The visual PDM network identifies the longest continuous path through the project which forming the critical path;

A → B → C → E → F, with a cumulative expected duration of 27.33 months.

Task D, although necessary, does not fall on the critical path and holds slack, calculated as the difference between the latest and earliest possible start times without impacting overall project completion. In other words, when Task D takes a tea break, Task C keeps the factory buzzing. This allows resource reallocation or rescheduling without triggering a project delay.

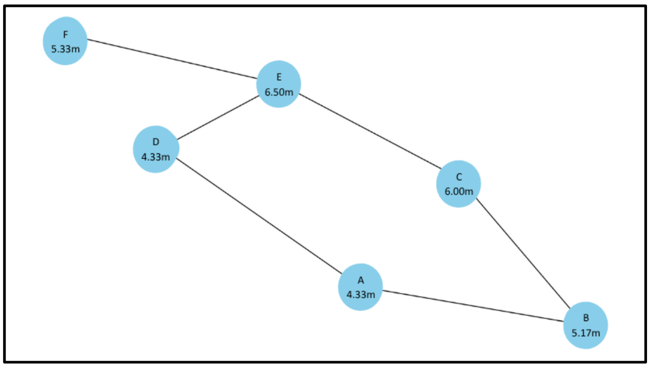

Fig. 1. PDM Network Based on TE Estimates

PDM forms the logical foundation of modern project scheduling software including Microsoft Project which operationalizes task relationships through Finish-to-Start, Start-to-Start, and other dependency types to compute critical paths and schedule floats [15]. Tools like Microsoft Project not only support PDM, they breathe it. Every click on a Gantt chart is a live PDM calculation in action. The Network Diagram in Microsoft Project represents the visual on a node-based diagram.

3.2.3 S-Curve Tracking

Cumulative TE values are plotted to generate a baseline S-Curve (Figure 2). This curve functions as the reference trajectory for tracking actual progress over time, with its baseline durations originating from PERT derived estimates and applied within the Earned Duration Management (EDM) framework. EDM framework is a methodology that decouples schedule tracking from cost data to focus on duration-based control [21]. Integrating EDM derived baselines into milestone-based planning models ensures that progress tracking remains anchored over budget weighted metrics [21]. Any deviation from this baseline will signal risk triggers and justify buffer activation. The S-Curve exposes early delays visually. For example, if by Month 10 only Tasks A and B are completed while Task C lags behind, the curve clearly reveals the deviation prompting immediate leadership attention. A schedule without warning signs is fiction. This model invites realism into the boardroom. While the analysis here remains deliberately concise, it serves the paper’s core objective which is to ground execution strategy at the planning stage. The focus shifts away from modelling every disruption in detail, instead equipping planners, managers and also the decision makers with early warning signals and structured response framework before complexity escalates.

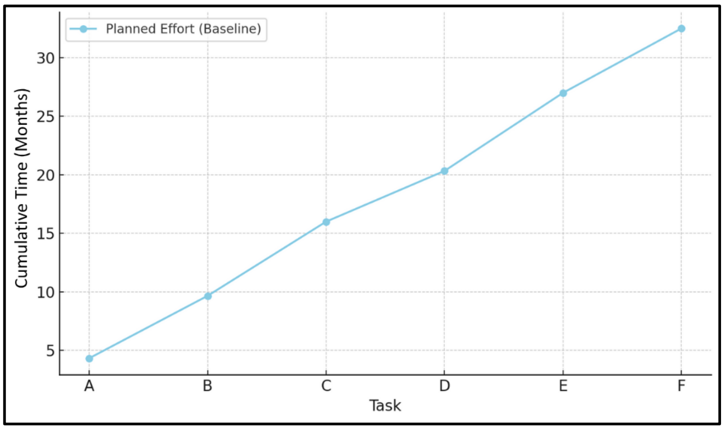

Fig. 2. S-Curve of Cumulative TE Based on Critical Path

This simulation showcases the integration of quantitative planning tools in a manner that transforms abstract planning into tactical decision making. Such digital twin aligned approaches have shown high relevance in aerospace manufacturing, particularly when combined with milestone forecasting and feedback loops [8], [13], [20]. It not only informs project leaders of timing constraints. It also prepares them for 'what if' scenarios where design iterations or supplier hiccups might stretch the timeline [13], [20].

S-curves are the heartbeat monitor of the timeline. A deviation may indicate trouble ahead, from supplier delays to engineering rework and provide empirical justification for resource mobilization or task resequencing.

3.2.4 Slack Zone and Buffer Allocation

Tasks not on the critical path, such as D, create schedule elasticity. This 'float' provides room for delays without domino effects. Such insight is invaluable when working with third-party or experimental components, both notorious for throwing wrenches into elegant schedules.

4. Discussion

This framework bridges policy with execution. It is built on established tools applied in a smarter, integrated manner to bring control and foresight into the early stage of aircraft development. Rather than promising perfection, it provides resilience. Leaders gain visibility in real time, course corrections can be made through simulation and deliverables remain aligned with national targets. In environment where delays are the norm rather than the exception, the framework offers discipline without rigidity.

4.1 Risk Handling through Embedded Controls

Every milestone includes embedded risk identification and mitigation checkpoints. For example, during prototype development, delays in component delivery can derail progress. Risk mitigation involves dual sourcing and rapid testing loops. Another example, unexpected changes in SAF policy may trigger design modifications. The model allows for gated reviews where course corrections are budgeted and documented. This model approach helps shift project management from reactive firefighting to proactive orchestration.

4.2 Scenario-Based Comparisons
4.2.1 Delay Scenario Analysis

To test schedule resilience, a three-months delay in Prototype Design (Task C) due to unexpected computational errors in aerodynamic modelling, was simulated. This shifts its TE from 6.00 to 9.00 months, extending the overall project duration from 27.33 to 30.33 months. Because Task C lies on the critical path, this delay affects all downstream tasks. By contrast, a delay in Component Procurement (Task D), which carries float, had minimal impact on the overall schedule. Mitigation measures for the Prototype Design (Task C) delay include fast-tracking parallel tasks, crashing resources into Prototype Construction (Task E) and adjusting buffers. These issues are also emphasised by Lytvyn *et al.* [8] who advocate for built-in coordination logic and adaptive controls to manage disruptions in aviation planning systems. Had the delay occurred in Task D, the impact would have been minimal, D possesses slack. However, for Task C that is a no-go zone for hiccups.

4.2.2 The Cost of Skipping PDM

Projects that neglect structured planning tools like PDM often default to static Gantt charts with oversimplified logic. These visuals may present clean task bars but hide complex interdependencies, leaving planners blind to float times, parallel paths and risk exposure. In a hypothetical case, skipping PDM led to;

i. Unnoticed critical dependencies
ii. Inability to reallocate resources dynamically
iii. Delayed detection of schedule slippage

By comparison, PDM enables visibility of task sequencing, slack identification and scenario simulation before execution. In short, it transforms project planning from guesswork to governance. It can be said that skipping PDM is like flying blind. The team would not know they are off-course until it is too late.

4.2.3 Traditional vs Structured Framework

Table 3 compares traditional Gantt-based planning against the integrated PERT-PDM-S-Curve framework proposed in this study. Features such as uncertainty modelling, float identification and dynamic monitoring clearly distinguish the proposed framework. The comparative features are adapted from Konior and Szostak [18] and PMI's scheduling standards [15], aligning the framework with academic research and industry best practice.

Table 3
Comparison of traditional Gantt chart vs integrated PERT-PDM-S-Curve framework.

Feature	Gantt	PERT-PDM-S-Curve Model
Dependency Logic	Basic (FS only)	Complex (FS, SS, FF, SF)
Uncertainty Modelling	Absent	Probabilistic (via PERT)
Critical Path Visibility	Hidden	Clear and quantified
Float/ Slack Identification	Manual	Automatic via PDM
Progress Monitoring	Static	Dynamic (S-Curve analytics)
Risk Forecasting	Weak	Built-in (buffers + variance)
Iteration Handling	Poor	Built-in (PDCA + milestone logic)
Software Support	Common (Excel, Gantt tools)	Supported in MS Project, Primavera
Planning Intelligence	Low	High

This structured framework, grounded in system-level discipline, supports real-time decision-making under uncertainty, a vital requirement in aviation innovation environments.

4.3 Strategic Leadership Relevance

In aircraft development, uncertainty and long lead times are unavoidable. The proposed framework equips decision-makers with visibility into critical delays, governance checkpoints for timely intervention and scenario planning to explore alternative pathways before committing. This shifts leadership from passive oversight to active orchestration, echoing the MAIB2030 call for agile governance and innovation clusters. In practice, the model allows leaders to pivot when suppliers delay, when certification rules are revised or when prototypes reveal flaws at the least convenient moment.

4.4 Result-Objective Alignment

The findings confirm that the integrated PERT-PDM-S-Curve framework meets its intended purpose. The model identified critical paths with statistical confidence, exposed float and buffer zones and flagged deviations through S-Curve tracking before they escalated into risks. These outcomes validate the framework's ability to strengthen early-stage planning discipline in low-emission aircraft development. In short, the result shows that the methodology is not a theoretical construct. It provides Malaysia with practical and resilient planning framework that embeds risk evaluation and mitigation across all milestone for translating vision into action. This aligns with Shin, Kim and Ko [19], who emphasise that effective project strategies embed risk evaluation and mitigation at each stage, allowing decision to be made with greater confidence before milestones advance.

5. Conclusion

This study set out to strengthen Malaysia's early-stage low-emission aircraft development planning by testing an integrated framework built on PERT, PDM and S-Curve analysis. The results demonstrate that the framework delivers its purpose. It identifies critical paths with statistical clarity, manage uncertainty through buffers and provides early warning signals before risks escalate. More importantly, it translates national ambitions for low-emission aviation into an actionable roadmap grounded in resilience rather than rigid timelines.

To operational the framework, the study mapped the model across four key milestones which are Study, Design, Construction and Commercialization. Each milestone is associated with distinct planning priorities, as summarized in Table 4.

Table 4
Model mapped across four strategic milestone

Milestone	Core Planning Focus
Study	Clarifying the problem landscape, identifying viable opportunities and building PERT-based scenarios to model development pathways under uncertainty
Design	Establishing the overall system architecture, resolving task and component dependencies using the PDM and finalising design specifications as a baseline for downstream integration sequencing
Construction	Tracking progress through S-Curve analysis, mitigating integration-related risks and progressively resolving high impact uncertainties prior to operational testing
Commercialization	Aligning with aviation regulators, synchronising with national SAF adoption timelines and executing a readiness-based implementation strategy that enables structured entry into certified operations

The framework therefore meets the study's objective of providing a structured yet adaptive tool for low-emission aircraft development in Malaysia. By embedding probabilistic forecasting, dependency mapping and progress tracking into a milestone-driven model, it offers leaders practical visibility to steer projects through turbulence without losing momentum.

To sustain competitive in hybrid aviation, it recommends that future work should validate the framework with real project data, extend its application to certification and supply chain integration and embed it into digital project management platforms for scalability. Adoption of such an approach will not only enhance governance discipline also provide a national edge in translating aerospace policy into operational success.

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