

INTEGRATING FACILITIES ENGINEERING AND RESEARCH INFRASTRUCTURE: A PROPOSED STRATEGIC FRAMEWORK FOR ADVANCING AEROSPACE TECHNOLOGY AT TUSKEGEE UNIVERSITY

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ABSTRACT

Aerospace research competitiveness depends on reliable, digitally connected, adaptable, and resilient infrastructure as well as faculty expertise and instrumentation. This paper proposes the Facilities-Engineering Integration Model (FEIM), a conceptual systems framework that links research strategy, capital planning, facilities engineering, digital engineering, laboratory operations, and workforce development. FEIM combines Building Information Modeling (BIM), Geographic Information Systems (GIS), Internet of Things (IoT) sensing, computerized maintenance and enterprise asset-management systems, and digital-twin methods in a common decision environment. Five performance tools are defined: the Facilities Research Readiness Index (FRRI), Research Infrastructure Return on Investment (RI-ROI), Infrastructure Resilience Index (IRI), Laboratory Utilization Efficiency (LUE), and Research Infrastructure Optimization Model (RIOM). The manuscript does not report completed empirical findings. Tuskegee University is presented as a proposed application context, and all numerical examples and metric weights are explicitly illustrative pending expert calibration and pilot validation. The revised methodology specifies units of analysis, sample targets, time horizons, confounder controls, a modified Delphi protocol, and a bounded pilot. Recent 2021-2025 smart-campus and digital-twin studies are used to distinguish FEIM from prior operational and visualization frameworks. A worked numerical example demonstrates how the metrics would be applied without representing institutional performance. The contribution is therefore a testable framework, implementation architecture, and validation plan rather than a completed case study.

KEYWORDS

Aerospace infrastructure, digital twin, facilities engineering, research infrastructure, smart campus, systems engineering

1. INTRODUCTION

Advanced aerospace research depends on a coupled system of people, instrumentation, laboratories, utilities, data, and operational processes. A laboratory with high-value equipment can still be research-constrained by unstable electrical service, inadequate ventilation, fragmented

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asset data, delayed maintenance, insufficient cyberinfrastructure, or capital investments that do not address the governing technical bottleneck. These dependencies become more consequential on legacy campuses where research growth, preservation, modernization, and constrained capital must be managed simultaneously.

Facilities organizations are usually evaluated through cost, facility condition, work-order response, energy consumption, deferred maintenance, compliance, and customer service. Those measures remain necessary, but they do not directly express whether a space can reliably support a funded research protocol, whether a critical utility has recoverable redundancy, whether research assets are accessible through a consistent digital thread, or whether capital projects improve the institution's ability to compete for sponsored work. This distinction motivates a research-readiness perspective rather than a building-condition perspective alone.

This paper proposes the Facilities-Engineering Integration Model (FEIM). FEIM treats facilities engineering as a component of the research enterprise and connects institutional strategy, research requirements, capital delivery, digital engineering, laboratory operations, workforce development, and performance assessment. The framework is intentionally conceptual at this stage. No pilot, Delphi panel, or longitudinal statistical analysis has yet been completed, and the paper therefore does not claim causal effects or measured institutional improvements.

Tuskegee University is used as a proposed application context because the manuscript's central problem is most visible where a historic physical plant must support contemporary engineering research. The conceptual contribution has four parts: (1) a systems architecture for facilities-research integration; (2) five testable performance measures; (3) a staged implementation and governance model; and (4) an empirical validation protocol that can be replicated across institution types. The revised paper also separates logical implications of the model from future empirical findings.

2. LITERATURE AND RESEARCH GAP

2.1. Digital Engineering and Lifecycle Integration

Digital engineering seeks to maintain authoritative, traceable information across the asset lifecycle rather than relying on disconnected drawings, spreadsheets, and work-order records. Building Information Modeling (BIM) structures geometric and asset information, while Geographic Information Systems (GIS) provide campus-scale spatial context for buildings, utilities, land, access, and environmental relationships. ISO 19650 establishes information-management principles for BIM-enabled delivery, and ISO 55000 and ISO 41001 provide complementary asset- and facility-management perspectives [2]-[5]. The U.S. Department of Defense digital-engineering strategy similarly emphasizes model-based continuity and authoritative sources of truth [1].

For research campuses, the central issue is not the existence of individual models. It is whether information can persist from planning through commissioning and operations, remain linked to unique assets, and support technical decisions. A common asset identifier and governed integration layer are therefore more important to FEIM than any single software platform.

2.2. Digital Twins, Smart Campuses, and Recent Empirical Evidence

Recent research has moved campus digital twins from broad concept toward implemented use cases. Han et al. developed a digital-twin-based intelligent campus system that connects campus

International Journal of Recent Advances in Mechanical Engineering (IJMECH), Vol.15, No.3/4, November 2026 management functions and virtual representations [9]. Ye et al. demonstrated an interactive campus digital twin for class distribution and building-capacity analysis at a large public university, showing a practical link between spatiotemporal institutional data and campus decisions [10]. García-Aranda et al. developed a university-campus digital twin in Madrid from an urban-sustainability perspective [11]. These studies demonstrate that campus-scale twins can integrate spatial information with institutional operations, but their primary decision targets are not research-infrastructure readiness.

Operational studies provide a second comparator. Domínguez-Bolaño et al. implemented an IoT platform across five real campus use cases involving air quality, environmental parameters, energy efficiency, photovoltaic production, and energy consumption, and documented interoperability, scalability, and data-management challenges [12]. Kang and Mo proposed and tested a building digital-twin framework focused on real-time connectivity and predictive monitoring [13]. Cespedes-Cubides and Jradi reviewed 21 building digital-twin use cases and identified common applications in monitoring, anomaly detection, operational optimization, predictive maintenance, and scenario simulation while also documenting persistent data-integration and BIM-dependency limitations [14]. Pavón et al. reported a BIM-based digital twin for university-campus management, providing a recent campus-specific facilities comparator [15].

Collectively, these studies provide empirical support for the use of digital twins, BIM, GIS, IoT, and operational analytics. They also sharpen the gap addressed here. The cited frameworks primarily optimize campus operations, building performance, sustainability, space, or data integration. FEIM instead asks whether those same digital and facilities capabilities can be organized around sponsored-research readiness, research continuity, laboratory use, capital prioritization, workforce development, and mission return.

2.3. Research Infrastructure and Institutional Competitiveness

Research infrastructure includes more than instruments. It includes the buildings, utilities, environmental systems, computing, networks, laboratories, technical staff, data systems, and governance needed to commission and sustain research capability. Current National Science Foundation programs such as Major Research Instrumentation (MRI), Mid-scale Research Infrastructure-1 (Mid-scale RI-1), and Campus Cyberinfrastructure (CC*) explicitly recognize instrumentation, cyberinfrastructure, and supporting institutional capacity as research enablers [23]-[25]. NASA, the Department of Defense, the Department of Energy, and the Federal Aviation Administration maintain complementary university research, capacity-building, advanced-manufacturing, energy, and aviation research pathways discussed in Section 7.4.

Conventional facility condition indices are not designed to capture this mission relationship. A building may be physically serviceable while lacking the environmental stability, power quality, network connectivity, equipment support, resilience, access, or configuration control required by a specific research program. FEIM therefore supplements, rather than replaces, facility condition, compliance, safety, and maintenance measures.

2.4. Research Gap and Distinction from Prior Frameworks

Table 1. Recent empirical comparators and the specific gap addressed by FEIM.

Study	Application context	Primary contribution	Gap relative to FEIM
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Study	Application context	Primary contribution	Gap relative to FEIM
Han et al. (2022) [9]	Intelligent campus	Digital-twin campus system architecture	Does not define research-readiness or capital-return measures.
Ye et al. (2024) [10]	Large public university	Class distribution and building-capacity visual analytics	Focus is space/capacity analysis rather than research-infrastructure strategy.
García-Aranda et al. (2024) [11]	University campus, Madrid	Campus twin for urban sustainability	Does not link facility decisions to sponsored-research outcomes.
Domínguez-Bolaño et al. (2024) [12]	University IoT platform	Five operational use cases and integration lessons	Operational sensing is not connected to research portfolio or capital prioritization.
Kang and Mo (2024) [13]	Building operations	Real-time connectivity and predictive monitoring	Building-scale performance rather than institution-scale research readiness.
Pavón et al. (2025) [15]	University campus management	BIM-based campus digital twin	Facilities-management focus; no integrated readiness, resilience, utilization, ROI, and optimization set.

The research gap is therefore narrower than a claim that digital twins or smart campuses are absent from the literature. The unresolved problem is how to convert facilities and digital-engineering information into a governed, testable research-infrastructure decision system. FEIM addresses that narrower gap by linking capital planning, operational reliability, laboratory utilization, research outcomes, and workforce development through common data and explicit performance measures.

3. FACILITIES-ENGINEERING INTEGRATION MODEL

FEIM is formulated as a closed-loop systems model. Research requirements initiate infrastructure decisions. Capital projects and operational interventions create or modify physical and digital capability. Asset, utility, laboratory, and research-use data then provide evidence about whether the capability performs as intended. Those observations inform maintenance, operating policy, and the next capital cycle. Figure 1 represents this feedback structure.

3.1. Research-Driven Capital Planning

Within FEIM, a capital need is defined by a research or mission requirement before it is defined by a construction solution. Candidate projects can then be compared using strategic alignment, research-continuity risk, regulatory and safety requirements, resilience, lifecycle burden, external funding leverage, digital contribution, and workforce value. This formulation is intended to expose utility, controls, environmental, commissioning, and data needs that can be obscured when prioritization relies on visible building condition alone.

3.2. Digital Infrastructure Integration

The digital domain uses BIM, GIS, the Internet of Things (IoT), computerized maintenance management systems (CMMS), enterprise asset management (EAM), building automation systems (BAS), and research-space data as interoperable components. FEIM does not assume that these systems must be replaced by a single platform. It requires that decision-critical assets have stable identities, traceable spatial locations, configuration and condition records, operational histories, relationships to research functions, and a capital-planning status. Figure 2 organizes these functions as layers rather than products.

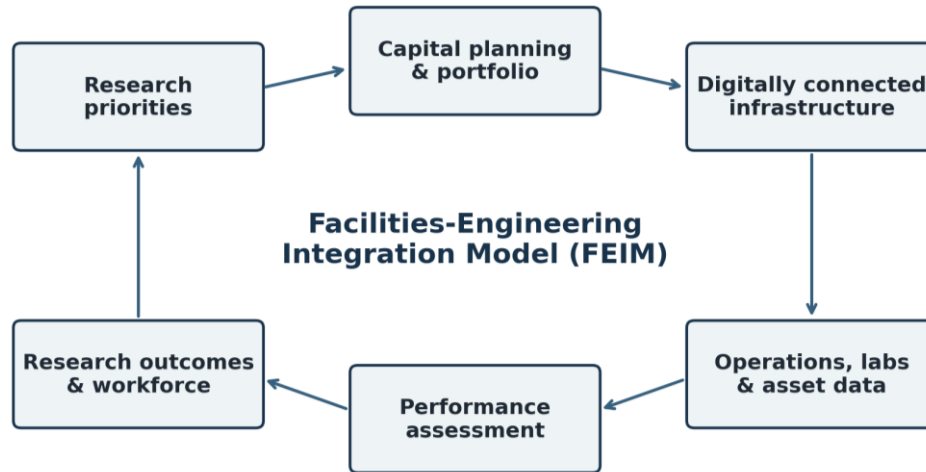


Figure 1. Facilities-Engineering Integration Model systems architecture. The diagram presents the conceptual feedback loop and does not represent measured causal effects.

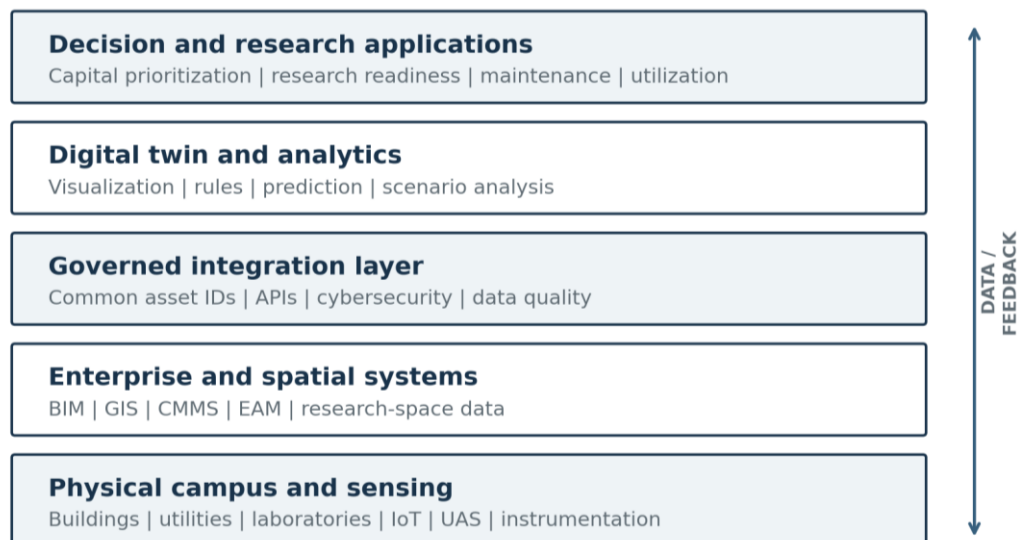


Figure 2. Conceptual campus digital-twin architecture. Each layer is governed by common identifiers, data-quality rules, and cybersecurity controls.

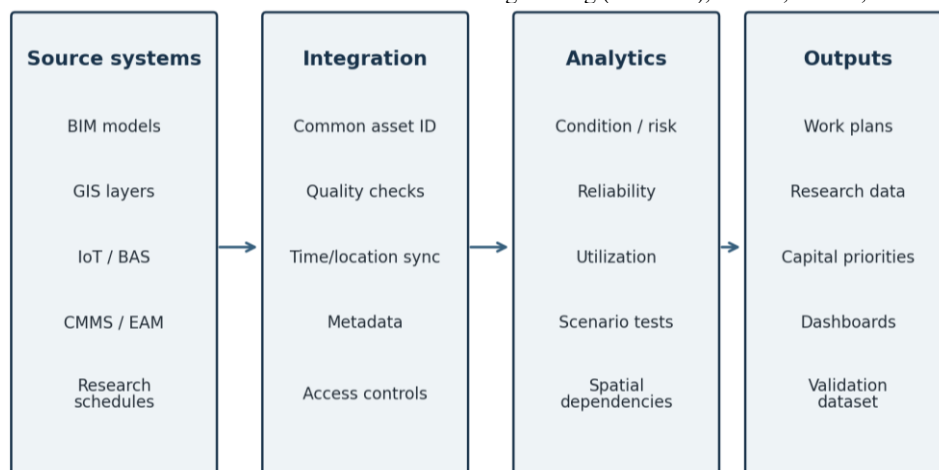


Figure 3. BIM-GIS-IoT integration workflow from source systems to research and facilities decisions.

3.3. Smart Research Platforms and Sensor Data Quality

FEIM treats selected buildings and utilities as potential research platforms when the operational data have a defined research purpose, quality standard, and stewardship plan. Relevant measurements can include structural response, energy, temperature, humidity, vibration, pressure, equipment state, occupancy, controls, and Unmanned Aircraft Systems (UAS) inspection data. The platform becomes a research asset only when sensor metadata, calibration, time synchronization, maintenance responsibility, data access, and retention are specified.

Remote-sensing inputs require the same discipline. Foundational remote-sensing practice distinguishes spatial, spectral or radiometric, and temporal resolution and emphasizes radiometric and geometric calibration before interpretation [19]. For FEIM, UAS imagery or other remote-sensing data entering the digital twin should therefore retain acquisition time, sensor characteristics, ground-control or positional metadata where applicable, calibration status, processing level, and uncertainty. This requirement prevents visually compelling imagery from being treated as decision-grade evidence without traceability.

3.4. Integrated Laboratories and Workforce Development

The laboratory domain links shared instrumentation, advanced manufacturing, computation, testing, and research-space planning to infrastructure operations. Shared resources can reduce duplication only if access, scheduling, maintenance ownership, environmental requirements, and lifecycle replacement are explicit. Workforce development is embedded in the model because students and technical staff can participate in supervised commissioning, BIM development, GIS mapping, UAS inspection, condition assessment, digital-twin programming, sensor validation, and predictive-maintenance analysis. These activities are treated as planned educational or research assignments, not as a substitute for qualified facilities labor or required professional oversight.

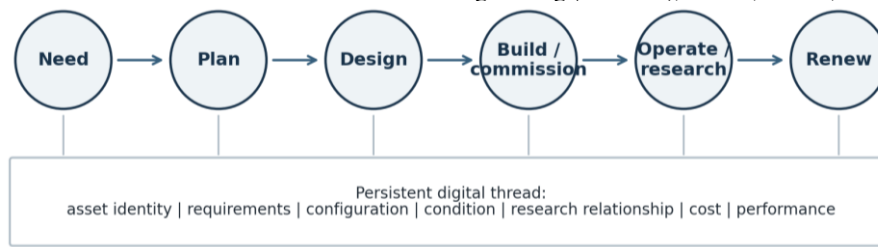


Figure 4. Research Infrastructure Digital Thread. Asset identity and requirements persist from need definition through renewal.

4. PROPOSED VALIDATION METHODOLOGY

The revised methodology separates framework development from empirical validation. The present manuscript represents the design-science artifact and proposed evaluation plan. Empirical claims will require completion of the data collection, expert review, and pilot described below. The validation design is mixed-method and longitudinal because no single data source can establish whether an infrastructure intervention improves research readiness.

4.1. Units of Analysis, Sample Targets, and Time Horizon

Table 2. Proposed validation design.

Component	Proposed sample	Primary unit	Time horizon	Purpose
Stakeholder interviews	12-18 purposively selected participants	Participant	One pre-pilot cycle	Refine requirements, barriers, and decision use cases.
Modified Delphi	18-24 experts in three balanced domains	Expert-rating item	Four rounds	Validate domains, metric definitions, and calibration approach.
Operational panel	20-40 critical assets and/or research spaces	Asset-space-month	12 months baseline + 24 months implementation/post	Estimate reliability, utilization, and time effects.
Pilot boundary	1 aerospace building, 1 shared laboratory, 1 critical utility, 1 digital-twin use case	Pilot system / month	36 months total where feasible	Bound implementation scope and document causal assumptions.
Capital sub-analysis	All candidate projects in one annual portfolio cycle	Project-year	At least one complete cycle; repeat annually	Test RIOM ranking, sensitivity, and decision traceability.

The primary quantitative unit is the asset-space-month because utility reliability, work orders, environmental stability, and utilization vary over time. A 20-40 unit panel observed for 36 months would yield approximately 720-1,440 unit-month records before missing-data exclusions. This is a planning target, not an achieved sample size. Statistical power and model complexity

International Journal of Recent Advances in Mechanical Engineering (IJMECH), Vol.15, No.3/4, November 2026 must be reassessed after the pilot inventory establishes actual variance, missingness, and serial correlation.

4.2. Data Sources and Integration

Planned data sources include building and utility inventories, facility condition assessments, work-order histories, equipment records, research-space assignments, laboratory schedules, sponsored-research activity, BAS trends, sensor records, project costs, commissioning records, and stakeholder interviews. BIM, GIS, CMMS, EAM, and sensor data will be joined through a governed asset registry. Each field used in a metric will have an owner, definition, source system, update frequency, quality flag, and retention requirement.

4.3. Statistical and Spatial Analysis

The initial analysis will report distributions, missingness, outliers, and temporal stability before any composite index is calculated. Correlation analysis will be used only for exploratory association. Where the panel is sufficient, fixed-effects or mixed-effects regression can evaluate relationships between infrastructure conditions and operational or research-use outcomes while accounting for repeated observations. Interrupted time-series analysis will test pre/post level and slope changes. If a defensible nonpilot comparator exists, a difference-in-differences specification may be added.

Potential confounders will be recorded explicitly. These include changes in sponsored-research funding, faculty or technical staffing, academic-calendar effects, laboratory commissioning, major equipment replacement, planned shutdowns, large capital projects, occupancy changes, and campuswide utility events. Department or research-group fixed effects and time indicators can be used where sample size permits. Spatial analysis will identify utility dependencies, research clusters, access constraints, and concentrations of risk. The objective is not to force causal inference from a small pilot, but to document the conditions under which stronger inference becomes possible.

4.4. Metric Calibration and Sensitivity Testing

The weighting coefficients in the original manuscript are not treated as derived empirical parameters. In the revised formulation, weights remain symbolic in the governing equations and must sum to one within each benefit index. The numerical values used in Section 6.6 are retained only as provisional starting values for a worked example. During validation, Delphi participants will rate the importance and measurability of each component. A pairwise analytic hierarchy process (AHP) may then be used with the final panel to derive normalized weights and check judgment consistency [20]. Whether AHP or direct normalized expert ratings are used, the resulting weights will be subjected to one-at-a-time and Monte Carlo sensitivity analysis before institutional adoption.

4.5. Ethical, Security, and Data-Governance Considerations

Institutional, operational-technology, and sponsored-research data require role-based access, minimum-necessary disclosure, cybersecurity review, and de-identification where appropriate. Human-subject review will be obtained where required for interviews or Delphi participation. Cybersecurity is part of the design because connecting building controls, sensors, research equipment, and enterprise systems can enlarge the attack surface. No operational-control pathway should be exposed merely to satisfy a visualization requirement.

5. PROPOSED APPLICATION AT TUSKEGEE UNIVERSITY

This section is intentionally labeled a proposed application rather than a completed case study. It describes how FEIM could be instantiated at Tuskegee University and defines the boundary for future pilot work. The manuscript does not present measured Tuskegee asset scores, laboratory utilization data, or causal outcomes.

5.1. Institutional Context

Tuskegee University has a long tradition of applied engineering education and operates a historically significant campus containing academic, research, residential, agricultural, utility, and administrative assets. Its aerospace education and research mission creates simultaneous requirements for specialized laboratories, reliable utilities, digital engineering, lifecycle stewardship, and coordination among faculty, facilities, information technology, safety, finance, and capital delivery. That combination makes the institution a useful setting in which to test whether a facilities framework can support research strategy without separating modernization from campus stewardship.

5.2. Proposed Aerospace Research District

One proposed application is a research district that clusters complementary capabilities around existing engineering assets. Candidate functions include advanced manufacturing, aerospace structures, autonomous systems, digital engineering, smart materials, shared machine shops, high-performance computing, and collaborative faculty-student space. Under FEIM, the value of clustering would be tested through equipment sharing, utility dependencies, access, utilization, interdisciplinary project activity, and lifecycle cost rather than assumed from physical proximity alone.

5.3. Proposed Pilot Initiatives

The pilot would first establish a common asset registry and minimum digital-engineering standard for the selected boundary. A digital twin would then integrate the pilot building, one shared laboratory, and one critical supporting utility. Structural, environmental, energy, and equipment sensing would be added only where a defined facilities or research use case exists. Capital-project records, commissioning data, research-space schedules, maintenance data, and sponsored-research activity would be linked at the appropriate aggregation level. Students could participate under faculty and professional supervision in mapping, sensor validation, model development, inspection, and analysis.

5.4. Expected Outcomes and Falsifiable Tests

FEIM logically implies that better integrated information should improve visibility of research-critical assets and that investments targeted to documented bottlenecks should improve readiness. These are hypotheses, not findings. The pilot will test whether laboratory availability, environmental stability, utility reliability, work-order response, utilization, data completeness, and decision traceability improve relative to baseline. A finding of no material improvement, high implementation burden, or poor user adoption would count against the framework and should trigger redesign rather than be reclassified as success.

5.5. Generalizability and Boundary Conditions

The five FEIM domains are intended to be institution-agnostic, but implementation intensity is not. A large research university may operate an enterprise data lake, dedicated digital-twin staff, and a portfolio of specialized laboratories. A smaller institution may use a common asset register, selected GIS layers, CMMS exports, inexpensive sensors, and a single shared research facility. The framework therefore scales by data maturity and decision need rather than by prescribing a fixed technology stack.

Tuskegee's historic-campus context and status as a minority-serving institution shape local constraints, partnership opportunities, and stewardship requirements. Those characteristics are important to the proposed application but are not assumptions embedded in the equations. External validation should therefore include HBCUs, non-HBCU research universities, smaller teaching-research institutions, federal laboratories, and industry campuses. Cross-site analysis should test which domains and metric relationships remain stable and which require institution-specific calibration.

6. PROPOSED PERFORMANCE MEASURES

The following measures are proposed constructs. Each component is normalized to a 0-100 scale unless otherwise stated. Index values should not be reported as institutional performance until definitions, source data, weights, and thresholds have been validated. Composite scores supplement, but do not replace, code compliance, life-safety requirements, facility condition assessments, and engineering judgment.

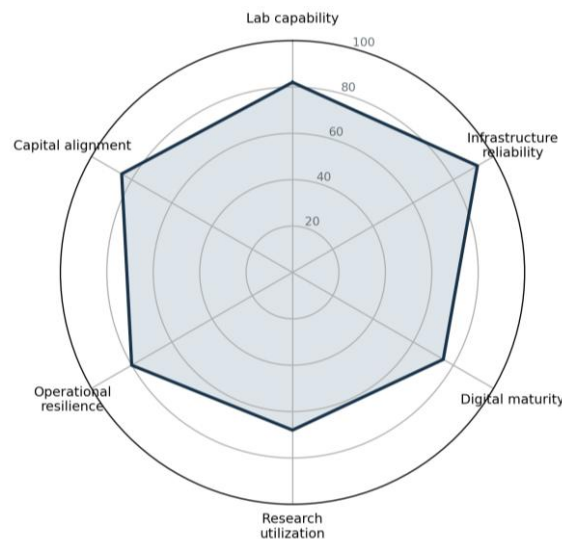


Figure 5. Illustrative FRRI dashboard with component units of 0-100. Values are hypothetical and are not measured Tuskegee University results.

6.1. Facilities Research Readiness Index (FRRI)

FRRI measures readiness across laboratory capability (L), infrastructure reliability (R), digital engineering maturity (D), research utilization (U), operational resilience (O), and strategic capital alignment (S).

$$FRR = \sum(w_j X_j), \text{ where } \sum(w_j) = 1 \text{ and } w_j \geq 0 \quad (1)$$

The general equation intentionally avoids universal fixed weights. A participating institution must publish the component definitions, calibrated weights, data sources, and sensitivity range used for each reporting period.

6.2. Research Infrastructure Return on Investment (RI-ROI)

$$RI-ROI = (G + P + I + W) / C \quad (2)$$

G is sponsored-research value attributable to the infrastructure over the selected horizon; P is monetized or shadow-valued publication, intellectual-property, and commercialization benefit; I is industry-partnership value; W is workforce-development value; and C is lifecycle infrastructure investment. RI-ROI is not an accounting return unless all numerator terms are direct financial flows. Any shadow valuation must be disclosed and sensitivity-tested separately.

6.3. Infrastructure Resilience Index (IRI)

$$IRI = w_R R + w_D D + w_{C_r} C_r + w_A A, \text{ where } w_R + w_D + w_{C_r} + w_A = 1 \quad (3)$$

R is reliability, D is redundancy, C_r is recovery capability, and A is adaptive capacity. The reliability component is written explicitly as:

$$R = 100 \times T_{up} / (T_{up} + T_{ud}) \quad (4)$$

where T_{up} is observed operating time and T_{ud} is unplanned downtime during the same measurement window. Redundancy is the percentage of critical functions with a tested backup path, recovery capability compares actual restoration time to an approved recovery objective, and adaptive capacity is scored with a documented rubric covering alternate spaces, remote operation where applicable, cross-trained personnel, temporary utilities, and emergency logistics. All component definitions require pilot calibration.

6.4. Laboratory Utilization Efficiency (LUE)

$$LUE = w_t U_t + w_e U_e + w_p P_r + w_c C_a, \text{ where } w_t + w_e + w_p + w_c = 1 \quad (5)$$

U_t is temporal utilization, U_e is equipment utilization, P_r is research productivity relative to an approved target, and C_a is capacity alignment. The metric is designed to avoid equating occupancy with productivity. A laboratory can score poorly because it is persistently underused or because demand materially exceeds safe, supportable capacity.

6.5. Research Infrastructure Optimization Model (RIOM)

The RIOM is revised to separate normalized benefit weights from lifecycle burden. This resolves the normalization problem in the original equation, where a negative cost coefficient was mixed into a set of positive benefit weights.

$$B_i = b_S S_i + b_F F_i + b_R R_i + b_W W_i + b_D D_i, \text{ where } \sum(b_k) = 1 \quad (6)$$

$$\text{maximize } Z = \sum[x_i (B_i - \lambda K_i)] \quad (7)$$

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For project i , x_i is a binary selection variable; S_i is strategic alignment; F_i is funding leverage; R_i is risk reduction; W_i is workforce value; D_i is digital contribution; K_i is normalized lifecycle burden; and λ is a separately calibrated burden penalty. The model remains subject to budget, annual cash-flow, staffing, space, dependency, mission-minimum, and portfolio-risk constraints. Integer or goal programming can be applied after the scoring model has been validated.

6.6. Worked Illustrative Example

To demonstrate the mechanics requested by the reviewers, consider a hypothetical modernization of an “Aerospace Structures and Digital Fabrication Laboratory.” The values below are deliberately illustrative. They are not Tuskegee University measurements, they do not represent a completed pilot, and the provisional weights have not been expert-validated.

Table 3. Worked illustrative example of FEIM metrics.

Metric	Illustrative inputs	Provisional calculation	Illustrative result
FRRI	L=82, R=92, D=75, U=68, O=80, S=85; weights 0.20/0.20/0.15/0.15/0.15/0.15	$0.20(82)+0.20(92)+0.15(75)+0.15(68)+0.15(80)+0.15(85)$	81.0 / 100
IRI	R=96, D=80, C _r =75, A=70; provisional weights 0.30/0.25/0.25/0.20	$0.30(96)+0.25(80)+0.25(75)+0.20(70)$	81.55 / 100
LUE	U _t =72, U _e =65, P _r =78, C _a =82; provisional weights 0.30/0.25/0.25/0.20	$0.30(72)+0.25(65)+0.25(78)+0.20(82)$	73.75 / 100
RI-ROI	G=\$1.10M, P=\$0.20M, I=\$0.35M, W=\$0.25M, C=\$1.50M	$(\$1.10+\$0.20+\$0.35+\$0.25)\text{M} / \$1.50\text{M}$	1.27 (illustrative)

The example shows why calibration matters. An FRRI of 81.0 has no independent meaning until the component definitions, weights, thresholds, and measurement uncertainty are validated. The same is true of an RI-ROI of 1.27 because publication, industry, and workforce benefits may require shadow valuations rather than direct revenue. The example is therefore a transparency device, not evidence of performance.

For RIOM, the original positive coefficients can be normalized to sum to one for demonstration: $b_S=0.278$, $b_F=0.222$, $b_R=0.222$, $b_W=0.167$, and $b_D=0.111$. With $\lambda=0.25$ as a provisional burden penalty, three hypothetical projects yield the comparison in Figure 6. These values are included only to show that the cost penalty is analytically separate from the normalized benefit weights.

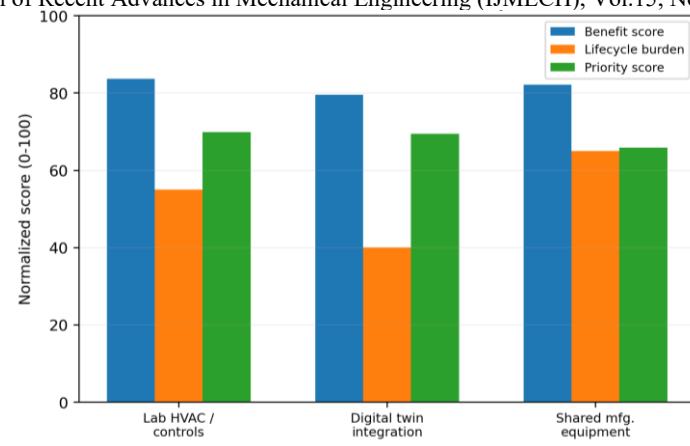


Figure 6. Illustrative RIOM portfolio comparison. All scores and lambda are hypothetical; vertical axis is a normalized 0-100 score.

7. IMPLEMENTATION, GOVERNANCE, AND FUNDING IMPLICATIONS

FEIM implementation is best treated as staged organizational learning rather than a campuswide technology deployment. The sequence below is a proposed research and implementation pathway. Progression between stages should depend on validated use cases, data quality, user adoption, cybersecurity review, and demonstrated decision value.

7.1. Five-Year Staged Roadmap

Table 4. Proposed five-year FEIM roadmap.

Year	Primary objective	Evidence required before expansion	Representative outputs
1	Digital foundation and governance	Common identifiers, owners, minimum data standard, baseline measures	Asset registry, GIS/BIM inventory, research-space inventory, governance charter.
2	Bounded digital-twin pilot	Stable data feeds, defined use cases, cybersecurity approval, user adoption	Pilot twin, dashboards, reliability and utilization baseline, data-quality report.
3	Aerospace research integration	Pilot evidence that data support research or operations decisions	Selected sensing, UAS inspection, shared lab integration, supervised student research.
4	Enterprise optimization	Validated metrics and documented benefit from multiple use cases	Predictive maintenance, capital forecasting, construction digital thread, portfolio analytics.
5	Replication and external validation	Cross-site protocol and reproducible data definitions	Implementation toolkit, benchmark study, multi-institution research, technology transfer.

7.2. Governance Model

Strategic authorization remains with institutional executive leadership and the governing board as appropriate. A cross-functional steering committee should establish policy, risk tolerance, portfolio priorities, and performance thresholds. A research-infrastructure council can manage technical standards, laboratory planning, digital integration, and data governance. Technical working groups should be created only for decision-critical functions such as digital twins, cybersecurity, asset management, aerospace applications, construction innovation, or research data. This structure separates policy authority from technical stewardship and project execution.

7.3. Change Management and Adoption

The principal implementation risk is not model creation. It is maintaining trustworthy data and making the integrated environment useful enough that researchers, facilities staff, information-technology personnel, and capital teams use it in routine decisions. Training should therefore be role-specific. Facilities personnel may need asset-data and sensor workflows; research teams may need data provenance and access rules; students may need supervised BIM, GIS, UAS, analytics, or commissioning tasks. Adoption should be measured through data completeness, active use cases, decision references, and user feedback rather than through the number of dashboards created.

7.4. Federal Funding Alignment: Current Program Families

The federal-program discussion has been updated to avoid presenting obsolete solicitation titles as permanent funding sources. The program families below were verified against current agency program pages as of August 16, 2026. Eligibility, open/closed status, deadlines, cost share, and allowable costs remain solicitation-specific and must be rechecked at the time of proposal preparation.

For the National Science Foundation, relevant pathways include the Major Research Instrumentation (MRI) program, Mid-scale Research Infrastructure-1 and -2, and Campus Cyberinfrastructure (CC*) [23]-[26]. NSF's current MRI and Mid-scale RI-1 pages indicate new or updated solicitation activity for the FY 2027 cycle, reinforcing the need to use the current program page rather than a static solicitation number.

For NASA, the Minority University Research and Education Project (MUREP) remains a current capacity-building umbrella for minority-serving institutions. Depending on the annual call, related pathways can include MUREP research-infrastructure and capacity-building opportunities, the University Leadership Initiative (ULI), and Space Technology Research Grants (STRG) [27]-[29]. For the Department of Defense, the Defense University Research Instrumentation Program (DURIP), Multidisciplinary University Research Initiative (MURI), and HBCU/Minority Institution research and education opportunities remain relevant program families [30]-[31].

For the Department of Energy, the Advanced Materials and Manufacturing Technologies Office (AMMTO) currently supports competitive research and development in advanced manufacturing, including smart-manufacturing themes, while the Office of Electricity maintains microgrid and grid-resilience activities [32]-[33]. For the Federal Aviation Administration, current pathways include Aviation Research Grants, Air Transportation Centers of Excellence, and aviation-workforce grant programs; UAS and advanced-air-mobility research can also align with FAA centers and research priorities [34]-[35]. FEIM does not assume that every platform is eligible for

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every agency. A proposal must establish a direct research question and allocable cost relationship rather than treating the digital twin as a generic funding vehicle.

A coordinated funding strategy can still reduce fragmentation if a shared institutional platform is separated from agency-specific research scope. For example, common asset identifiers and a secure data architecture may be institutional infrastructure, while a NASA or DoD project funds only the research sensors, models, experiments, or personnel needed for its approved statement of work. This distinction is necessary to prevent duplicate charging and to preserve long-term stewardship after individual awards end.

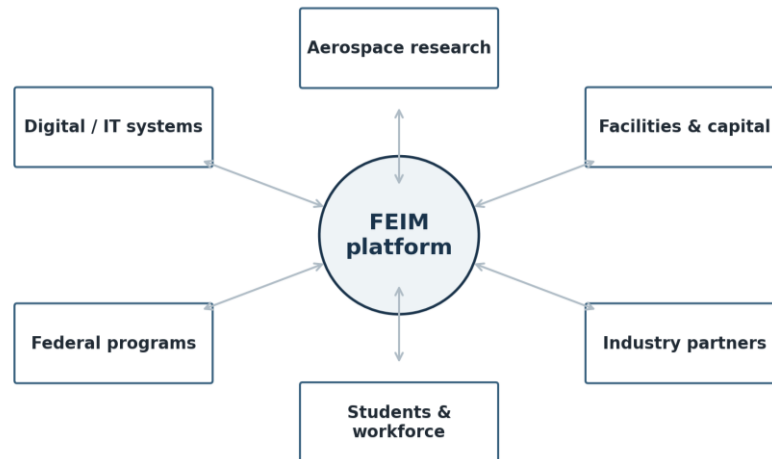


Figure 7. Conceptual aerospace innovation ecosystem enabled by FEIM. Arrows represent information and collaboration pathways, not contractual relationships.

8. CONCEPTUAL IMPLICATIONS, TESTABLE PROPOSITIONS, AND LIMITATIONS

8.1. Logical Implications of the Framework

The following statements are logical implications of FEIM, not empirical findings. First, a common asset and research-data structure should make dependencies among laboratories, utilities, equipment, and capital plans more visible. Second, explicit readiness and resilience measures should make research-continuity risk easier to compare across candidate investments. Third, a digital twin should have greater institutional value when it is tied to repeatable decisions than when it exists primarily as a visualization product. Fourth, a living-laboratory model should produce more durable educational value when data quality, access, maintenance, and faculty ownership are established before sensor deployment.

8.2. Testable Propositions for the Pilot

- P1.** Higher validated FRRI scores will be associated with higher research-space availability and fewer infrastructure-caused interruptions, after controlling for time and major capital events.
- P2.** Higher IRI scores will be associated with lower unplanned downtime and shorter recovery time for research-critical functions.
- P3.** Implementation of the governed BIM-GIS-IoT integration layer will improve asset-data completeness and reduce time required to assemble information for selected facilities and capital decisions.

- P4.** LUE will identify both persistent underuse and demand-capacity mismatch more accurately than occupancy rate alone when compared with laboratory schedules and equipment-use records.
- P5.** RIOM rankings will remain materially stable across reasonable weight ranges; if rankings reverse frequently under sensitivity analysis, the model should not be used as a deterministic capital-priority score.

8.3. Limitations and Failure Modes

The largest limitation is lack of empirical validation. Composite indices can create false precision if definitions or weights are weak. Small pilot samples can also produce unstable regression estimates and confound intervention effects with funding, staffing, or calendar changes. Digital integration can add cost without improving decisions, and a sophisticated platform can become obsolete if stewardship is not funded. Cybersecurity risk can increase when operational technology is connected to enterprise analytics. Faculty and facilities personnel can experience added workload if data stewardship is treated as an incidental duty.

These failure modes are part of the evaluation. FEIM should not be scaled merely because a pilot can be technically built. Scale should follow evidence that the selected use cases improve a documented decision, research-support outcome, or learning objective at a defensible lifecycle cost.

9. MODIFIED DELPHI AND PILOT VALIDATION PROTOCOL

9.1. Panel Composition

A modified Delphi panel of 18-24 experts is proposed. Representation should be approximately balanced among (1) facilities, capital, asset-management, or reliability leaders; (2) aerospace faculty, laboratory leaders, or research administrators; and (3) systems engineering, digital engineering, data, or digital-twin specialists. Participants should satisfy at least two qualification criteria, such as ten years of relevant experience, leadership of a major facilities or research program, peer-reviewed scholarship, professional licensure, digital-twin implementation experience, or federal-research program experience.

9.2. Four-Round Process

Round 1 will use open-ended review to identify missing elements, technical weaknesses, data requirements, implementation barriers, and unintended consequences. Round 2 will use five-point ratings for relevance, clarity, construct validity, feasibility, measurability, scalability, and institutional value. Round 3 will return anonymized group statistics and comments so participants can reconsider ratings. Round 4 will confirm the final architecture, metric definitions, calibration method, governance requirements, data fields, and readiness for pilot implementation. If AHP pairwise comparisons are used for metric weighting, they will be conducted only after the component set is stable.

9.3. Consensus and Reliability

$$\text{Median}_j \geq 4.0, \text{IQR}_j \leq 1.0, \text{and Agreement}_j \geq 75\% \quad (8)$$

Items satisfying all three criteria will be retained. Items without consensus will be revised, combined, removed, or designated for further testing. Cronbach's alpha of at least 0.70 may be

International Journal of Recent Advances in Mechanical Engineering (IJMECH), Vol.15, No.3/4, November 2026 reported for internally coherent multi-item scales, but it will not be treated as evidence of content validity by itself. Results will also be reviewed by expert domain because pooled agreement can conceal systematic differences between researchers, facilities practitioners, and digital specialists.

9.4. Pilot Validation and Decision Rule

Following expert validation, the bounded pilot will include one aerospace building, one shared laboratory, one critical utility, one digital-twin use case, and one capital decision cycle. Monthly baseline and post-implementation measures will include unplanned downtime, response time, environmental stability, laboratory utilization, researcher satisfaction, student participation, data completeness, selected proposal activity, FRRI, IRI, and LUE. The pilot will document a comparison period and, where feasible, a matched nonpilot system. Expansion will require evidence of data reliability, user adoption, a meaningful decision or operational benefit, acceptable cybersecurity risk, and lifecycle supportability.

10. CONCLUSIONS AND FUTURE RESEARCH

FEIM is a proposed facilities-research integration framework, not a completed empirical study. Its contribution is to define a testable institutional architecture in which research requirements can influence capital planning, digital engineering, facilities operations, laboratory use, and workforce development through a common data thread. The revised manuscript removes unsupported claims of results, parameterizes unvalidated metric weights, normalizes RIOM benefit coefficients, provides an explicit reliability formula, specifies the planned sample and time horizon, and demonstrates the metrics with clearly labeled hypothetical values.

The next research step is empirical. The modified Delphi panel should validate the construct set and calibration approach before the pilot begins. The bounded pilot should then establish data quality, baseline variability, implementation burden, and whether the proposed measures respond to meaningful changes in research-support infrastructure. Longitudinal and cross-institution validation will be needed before thresholds or universal weights can be proposed.

Future work should compare FEIM across HBCUs, non-HBCU research universities, smaller institutions, federal laboratories, and aerospace industry campuses. Additional research should address cybersecurity, interoperability, lifecycle cost, organizational adoption, sensor uncertainty, and causal relationships between infrastructure investment and sponsored-research outcomes. A useful FEIM implementation will ultimately be judged not by the sophistication of its digital twin, but by whether it produces more reliable evidence for research, facilities, and capital decisions.

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MANUSCRIPT STATUS NOTE. *All worked numerical values and Figures 5-6 are illustrative. No empirical Tuskegee University performance results are reported in this manuscript.*

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