A CPM-BASED FRAMEWORK FOR MANAGING DIGITAL TRANSFORMATION IN SMART LABS

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Abstract

This study proposes a conceptual framework for implementing smart laboratory platforms, integrating the Critical Path Method (CPM) to optimize development timelines and resource allocation. The framework addresses the design, sequencing, and interdependencies of digital infrastructure components, ensuring alignment with institutional objectives and research needs. By modeling tasks as a directed acyclic graph, CPM identifies the sequence of activities that determine the minimum completion time, distinguishes critical from non-critical tasks, and quantifies scheduling flexibility. A case study demonstrates the application of CPM in planning a smart lab platform, highlighting key dependencies, potential bottlenecks, and opportunities for workload balancing. The findings provide actionable insights into project scheduling, risk management, and stakeholder coordination, offering a structured methodology adaptable to diverse institutional contexts.

Keywords: smart labs, critical path method, workflow optimization, digital infrastructure

JEL Classification: O32

1. Introduction

The transition toward smart laboratories is driven by the increasing integration of digital technologies, automation, and data-driven decision-making in research environments. These platforms combine hardware, software, and networked services to enhance operational efficiency, enable remote collaboration, and support complex experimental workflows. However, the deployment of such systems presents significant challenges, including the coordination of multiple interdependent tasks, alignment with institutional strategies, and the optimization of time and resource allocation.

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This study addresses that gap by proposing a conceptual framework that integrates digital infrastructure planning with workflow optimization using the Critical Path Method (CPM). Rather than serving merely as a project management tool, CPM is applied as a process modeling technique to capture task dependencies, sequence activities logically, and identify implementation bottlenecks. The resulting framework spans technical, operational, and organizational layers, offering a scalable and interoperable model for planning and deploying smart labs. This contribution advances existing literature in project scheduling, research infrastructure, and digital transformation by introducing formal process dependency analysis into laboratory design.

To facilitate a structured analysis, the article is organized into several key sections. It begins by contextualizing smart laboratories within the broader landscape of digital transformation and research infrastructure. It then presents the theoretical foundation and modeling rationale, followed by a detailed explanation of the proposed framework, the use of CPM, and the implications for implementation and scalability. The final sections discuss the practical significance, limitations, and directions for future empirical validation.

From a practical perspective, the framework provides a planning and management tool for laboratory designers, IT architects, and academic institutions. It supports better coordination, scheduling, and integration of digital components while enabling modular development, operational flexibility, and institutional scalability.

To structure this investigation, the study pursues three primary objectives:

• to develop a conceptual framework for the design and implementation of smart lab environments, integrating digital infrastructure with workflow optimization;

• to apply CPM as a modeling technique to map dependencies, identify bottlenecks, and optimize resource allocation;

• to analyze existing frameworks and propose an integrated solution that enhances scalability, interoperability, and operational efficiency in smart lab systems.

Methodologically, this research follows a qualitative, design science approach, grounded in conceptual frameworks and informed by a synthesis of relevant literature. Workflow mapping is used to visualize how hardware, software, and data systems are integrated within the smart lab environment. The resulting framework spans technical, operational, and organizational layers, offering a coherent model that is adaptable to institutional realities.

Although conceptual at this stage, the framework is consistent with design science research standards and provides a transferable foundation for future empirical validation. It offers both a theoretical advancement in structured smart lab planning and a practical tool for institutions undergoing digital transformation. Unlike existing procedural guides or case-specific implementations, this framework introduces a generalizable, theory-driven methodology for planning smart labs.

2. Literature review

2.1 Smart labs: virtualization and digitalization

In this study, a smart laboratory refers to a digitally integrated research environment that combines hardware, software, and data infrastructure to support real-time, collaborative, and automated research processes.

Smart laboratories increasingly utilize IoT, AI, and digital technologies to support adaptive experimentation and scalable learning [1]. Their growing complexity necessitates not only advanced infrastructure but also structured educational approaches. To address this, Zamiri et al.[2] propose a training toolkit to integrate Smart Labs into academic curricula, aligning with learner and institutional needs. Modularity and interoperability are also key, as Gawer [3] argues, to support cross-institutional collaboration and innovation. Additionally, Zvobgo [4] emphasizes the need for stakeholder alignment, governance, and outcome-based planning. These insights collectively advocate for a holistic smart lab framework that integrates technological, pedagogical, and strategic elements to enhance educational and research outcomes.

The SMART-UHA Project [5] underscores the integration of university campuses as open innovation ecosystems where students, researchers, and industries co-develop technologies in real-world contexts. It emphasizes participatory engagement and modular infrastructure, aligning with our framework's emphasis on stakeholder involvement and interoperability.

Zheng et al. (Zheng et al., 2019) propose an IT-driven co-creation paradigm through "smart, connected open architecture products," advocating for lifecycle personalization and dynamic reconfiguration. Their model supports our framework's scalability and modularity, especially in terms of adapting digital platforms to user needs and extending smart lab capabilities across the research lifecycle.

The Siemens roadmap [8] and the U.S. DOE Smart Labs initiative [9] both highlight infrastructure readiness and energy efficiency but lack comprehensive methodologies for integrating digital tools with research workflows. These sources validate our argument for a structured implementation framework that merges project scheduling with technological architecture.

Backlund et al. [10] highlight the challenges of implementing smart labs in multipurpose environments, pointing to the necessity of pilot testing, stakeholder co-creation, and infrastructure adaptability. This reinforces our proposal to empirically test the conceptual model through simulations and pilot programs.

Bygholm and Kanstrup [11] critique the participatory models in living labs, suggesting that without structured methodologies, engagement remains superficial. This lends further weight to our framework's layered approach, where design science principles ensure systematic stakeholder engagement and repeatable planning models.

Smart laboratory implementation faces several challenges. Key among them is the need to enable remote operability and multi-user access, which underscores the importance of automation and digitalization [12]. Additional barriers include limited access to necessary electronic components, regulatory constraints on imports, procurement delays, and unstable internet connectivity [13].

2.2. Frameworks in Smart Labs

Despite a growing body of case studies [14] and institutional initiatives on smart lab development, the literature still lacks comprehensive, generalizable frameworks that integrate key elements such as scheduling logic, interoperability, and stakeholder engagement. While standards like ISO/IEC 15288 and the SiLA [15] interface emphasize lifecycle management and semantic interoperability, they are rarely applied in practice to guide smart lab implementation. Existing models often focus narrowly without addressing platform orchestration or integrated workflows.

Major industry reports, like those from Siemens [8], underscore the importance of infrastructure modernization but stop short of offering holistic methodologies for aligning digital infrastructure with research-specific needs. Similarly, the I2SL Smart Labs Toolkit [14] prioritizes energy and ventilation optimization over collaborative or scalable implementation models. Projects often begin with retrofitting existing infrastructure, leading to compatibility issues with legacy systems and fragmented interfaces [16], [17].

To address these theoretical and methodological limitations, this study introduces a CPM-based framework that bridges digital infrastructure planning with structured process execution, offering a more repeatable and adaptable approach for the development of smart laboratories.

2.3. The Context and Value of CPM in Smart Labs

CPM provides a structured approach for managing the complexity of smart lab development, where system interoperability, digital infrastructure, and testing phases are highly interdependent. Originating in the 1950s from engineering and construction project management [18], CPM identifies the longest sequence of dependent activities to determine the minimum project duration [19].

While CPM does not address concurrent scheduling or resource constraints, it remains essential in identifying bottlenecks and prioritizing critical tasks. This makes it particularly valuable for digital transformation initiatives like smart labs, where delays in key implementation stages—such as system integration or testing—can disrupt the entire timeline [20], [21], [22]. Zheng et al. [23] in their review on smart manufacturing systems for Industry 4.0, argue for integrating modular platforms and AI-driven optimization. Their perspective supports the adoption of scheduling tools like CPM for enhancing task prioritization and process automation in smart labs.

3. Methodology

The research design combines two complementary methodological components: literature-based conceptual synthesis and dual-layered process modeling. A structured literature review was conducted to identify current challenges, implementation strategies, and technological best practices in smart lab development. The review focused on areas such as digital infrastructure design, workflow optimization in research contexts, and the application of scheduling methodologies in complex environments.

- Task Identification and Structuring: Project activities were defined based on institutional requirements, technical specifications, and stakeholder input. Eleven major tasks were identified, covering hardware/software acquisition, technical requirements specification, technology development, platform security, data management, authentication, user interface design, system integration, testing, protocol development, and deployment with training.
- Dependency Mapping: A directed acyclic graph was constructed, where each node represented an activity and each edge indicated a dependency. This ensured logical sequencing by linking each task to its immediate predecessors and successors. The structure also allowed for the identification of concurrent and sequential tasks, enabling the differentiation between critical and non-critical activities.
- Duration Estimation: Published literature and industry reports on smart laboratories and digital infrastructure initiatives were consulted to extract typical implementation patterns, expected challenges, and development timelines. These sources helped refine both the activity categories and their temporal expectations, ensuring that the framework reflects practical constraints and industry norms.
- Critical Path Analysis: A forward pass calculation determined the earliest start (ES) and earliest finish (EF) for each activity, while a backward pass established the latest start (LS) and latest finish (LF) times. Total float was computed as the difference between LS and ES (or LF and EF). Activities with zero float were identified as critical.

The analysis revealed a critical path with a total duration of 23 months. Non-critical activities exhibited float values that allow rescheduling without affecting the overall completion date. This distinction provides opportunities for resource leveling and risk mitigation.

The resulting CPM diagram (Figure 2) and Gantt chart (Figure 3) visually represent the temporal and logical structure of the project, enabling clear communication of scheduling priorities to all stakeholders.

4. Results and discussions

The smart lab platform, as defined in this study, refers to the integrated digital infrastructure that supports and enhances the operation of laboratory workflows, including data management, task scheduling, and inter-system communication.

The proposed framework consists of five key implementation phases: (1) infrastructure and component assessment, (2) technology development and standardization, (3) security and access control, (4) system integration and implementation, and (5) testing and validation. Each phase is structured using CPM-based workflow modeling. The logical sequence of tasks, their interdependencies, and durations are represented through a directed acyclic graph to identify the critical path and optimize scheduling.

4.1. Structuring activities for a smart lab platform

The diagram presents the structured process extracted from the literature that we followed in designing the smart lab framework, divided into five key stages: infrastructure assessment (identifying technical readiness), development and standardization (aligning hardware/software), security and access control (data protection, access governance), system integration and implementation (platform assembly), and testing and validation (system performance). This visual representation reflects our conceptual model and serves to clarify the logical sequence and interdependencies between development tasks, as seen in Figure 1 below.

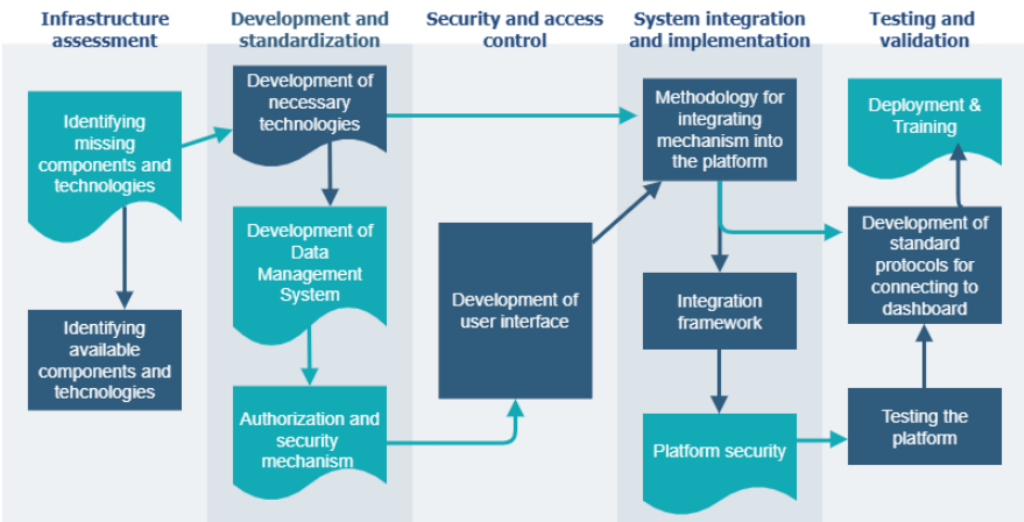

Figure 1. Key principles of a smart lab platform development workflow[3]

The conceptual model begins with **Infrastructure and Component Assessment**, which involves a comprehensive analysis of the existing infrastructure to identify both available and missing components, technologies, and potential integration points. This diagnostic step focuses on uncovering gaps in hardware, software, and connectivity that may affect system performance. The primary objective is to minimize development costs and reduce implementation time by leveraging existing resources while ensuring scalability and functionality of the platform.

In the **Technology Development and Standardization** phase, the necessary technologies are designed and developed to bridge the identified gaps. This phase emphasizes advancements in both hardware and software capabilities, the integration of AI-driven modules for automation and optimization, and the support for platform scalability. These foundational elements are essential to enable collaborative research and data-driven experimentation.

The **Security and Access Control** stage prioritizes the implementation of a robust authorization mechanism to manage authentication and role-based access. A user interface is developed to support intuitive navigation, secure experiment monitoring, real-time system interaction, and efficient access management. This interface serves as a bridge between users and the core infrastructure, ensuring usability alongside data protection.

During **System Integration and Implementation,** a standardized methodology is applied to integrate all platform components. This ensures technical compatibility across diverse hardware, software modules, communication protocols, and network systems. Security measures such as encryption, firewall protection, threat detection systems, and vulnerability assessments are implemented to preserve data confidentiality, integrity, and availability.

The final stage, **Testing and Validation**, includes the development of standardized communication protocols that enable seamless interaction between data sources, AI tools, and the user dashboard. A key outcome of this phase is the creation of an interactive dashboard that supports real-time experiment tracking, data analytics, and centralized reporting. This component enhances laboratory oversight and facilitates informed decision-making and efficient research execution.

4.2. Critical path method in smart lab platform development

To operationalize the planning logic, we developed a process framework based on CPM, detailed below.

The CPM activity set for smart lab implementation was developed through a systematic project management and systems engineering approach. Functional requirements were first identified—hardware setup, software development, data management, user interface design, integration, testing, and deployment—and translated into sequential, interdependent

[3] Realized using Draw.io https://draw.io

tasks. Dependencies were mapped using a directed acyclic structure, ensuring that prerequisite components, such as security systems and dashboards, follow foundational infrastructure development. Activity durations, estimated in months via expert input and benchmarks, reflect varying complexity, from short requirement identification phases to longer technology development stages. Eleven activities (A–K) were defined, with the critical path A → C → D → G → H → I → K determining the minimum project duration. This framework enables precise scheduling, highlights bottlenecks, and prioritizes zero-slack tasks to safeguard overall project timelines.

Activity ID	Activity (edges)	Dependency	Length (months)
A	Identify necessary hardware and software components	-	2
B	Authorization & Security Mechanism Development	A	3
C	Identification of Required Components & Technologies	A	2
D	Development of Essential Technologies	C	8
E	Development of Data Management System	A	5
F	User Interface & Dashboard Design	B	4
G	Platform Security Implementation	C, D	5
H	Integration of All Components into the Platform	E, F, G	1
I	Testing & Validation of the Smart Lab	H	3
J	Development of standard protocols for connecting to the dashboard	H	3
K	Deployment & Training	I, J	2

Table 1. Activity List with Dependencies and Estimated Durations for Smart Lab Platform Implementation.

However, to visualize these dependencies and structure workflow execution, we need a graph-based process model, as discussed in the next section.

4.3. Complex process modeling for smart lab platform

Building on the critical path structure identified in the previous section, we developed a graph-based process model to simulate the sequence and dependencies of smart lab implementation tasks.

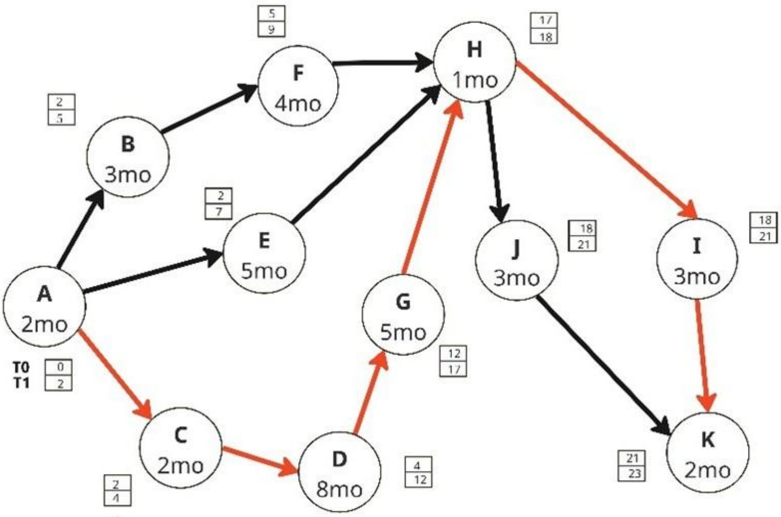

Figure 2. Critical Path Diagram: Visualizing task interdependencies and timeline (A–K) in smart lab platform implementation.[4]

To enhance the clarity and analytical depth of process modeling, the critical path analysis was supplemented with a detailed CPM diagram. The Critical Path Method is a formal project management technique widely used in engineering and operations planning to model the structure, timing, and dependencies of interrelated activities. In the context of smart lab development, the CPM diagram clearly represents task sequences, durations, and the distinction between critical and non-critical activities. Unlike simple workflow charts, CPM diagrams explicitly display logical task relationships, highlight the longest path through the project network, and indicate where float (slack) exists. This allows for precise coordination of activities such as user interface development, platform security, or integration under defined timing constraints.

The diagram in Figure 2 was constructed as a directed acyclic graph, where each node represents an activity and each directed edge denotes a dependency. Activity durations were estimated using expert input and comparable project timelines, assuming fixed resource availability and sequential execution. The CPM computation identified the critical path as

[4] Realized using Miro https://miro.com

A → C → D → G → H → I → K, with a total project duration of 23 months. All activities on this path exhibit zero total float, indicating that any delay will directly extend the project completion date.

Forward and backward pass calculations identified significant float in non-critical activities: E (Data Management, 10 months), B (Authentication & Security, 8 months), and F (UI & Dashboard, 8 months). These tasks can be rescheduled or resource-leveled without affecting overall delivery, provided they are completed by their latest start times (E: month 12, B: month 10, F: month 13). In contrast, D (Develop Technology) and G (Platform Security) represent primary bottlenecks due to their extended durations and critical positioning, while H (Integration) serves as a key convergence point for downstream processes I (Testing) and J (Protocol Development). Although J is non-critical, its timely execution remains essential for synchronized deployment alongside testing outputs.

This interpretation supports three strategic management actions:

- Prioritize resources for D and G to mitigate risks of delay.
- Leverage float in E, B, and F to optimize workload distribution.
- Implement readiness gates at H and I to ensure prerequisites are met before initiating dependent activities.

This CPM assessment not only quantifies the minimum feasible completion time but also provides actionable insights into schedule flexibility, resource allocation, and risk concentration, enabling data-driven decision-making for efficient project execution.

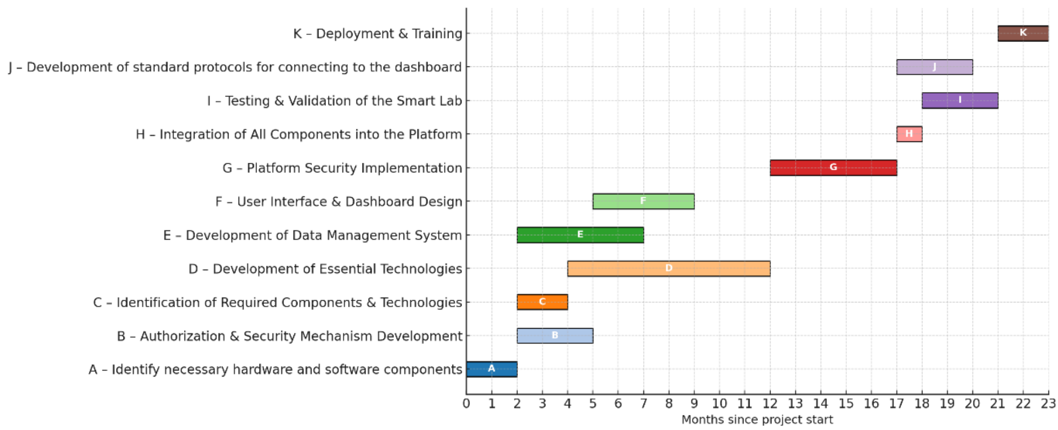

Figure 3: Gantt Chart for Smart Lab Implementation based on CPM Analysis

The Gantt chart in Figure 3 translates the CPM network into a time-scaled visual schedule, showing each activity's duration, start and end dates, and dependencies in a linear format. Critical path activities are highlighted to emphasize their impact on the overall schedule, while non-critical tasks are shown with their available slack. This visualization enables stakeholders to monitor progress, adjust non-critical activities, and focus resources on preventing delays in critical path tasks.

4.4. Implementation Considerations

Successful deployment of a smart lab platform requires more than technical integration; it also demands institutional alignment and coordinated stakeholder engagement. Key actors, including institutional leadership, IT personnel, lab coordinators, researchers, and administrative staff must align implementation with broader organizational goals across both operational and governance layers of the proposed framework.

Institutional leaders guide strategic planning and ensure policy alignment, while IT teams manage system interoperability and cybersecurity. Lab coordinators oversee functional workflows, and researchers contribute domain-specific requirements for experimental design and data handling. Involving these stakeholders early, particularly during infrastructure assessment and workflow design, enhances user adoption, promotes iterative refinement, and ensures long-term sustainability through compliance and governance integration.

5. Conclusions

This study introduces a conceptual framework for the digital transformation of smart laboratories, integrating the Critical Path Method (CPM) with workflow design and digital infrastructure strategies. The framework provides a scalable, secure, and interoperable roadmap for managing complex research environments and improving operational efficiency, resource allocation, and data integration.

The originality lies in adapting project scheduling techniques—traditionally used in industrial and construction domains—to smart lab implementation. By mapping dependencies and critical processes, our framework supports coordinated planning, risk mitigation, and modular deployment across diverse technical ecosystems.

Unlike existing models such as the I2SL Smart Labs Toolkit or the Siemens SmartLab Roadmap, which emphasize infrastructure and safety, this CPM-based approach introduces a process-oriented dimension that enables quantifiable monitoring of implementation performance and proactive identification of bottlenecks.

Future validation should involve empirical testing and scenario-based simulations under varying resource constraints. Suggested key performance indicators include reduced workflow setup time, improved resource utilization, increased system uptime, and measurable cost savings.

Ultimately, the framework offers both theoretical and practical value, complementing existing smart lab initiatives while advancing structured, data-driven methodologies for next-generation research infrastructures.

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