



# Future-Proofing in Hospital Infrastructure Systems: A Partial Least Squares Structural Equation Modeling Analysis of Institutional Drivers, Planning Mechanisms, and Design Capabilities



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**Abstract:** Hospital infrastructure systems represent one of the most complex categories of engineered systems, characterized by the tight integration of system configuration, technical subsystems, operational processes, and governance structures. Despite their structural durability, such systems—particularly in institutionally unstable environments—are prone to early functional and operational obsolescence, leading to performance degradation over the lifecycle. This challenge highlights the need to conceptualize hospitals not as static built assets, but as dynamic socio-technical systems requiring systematic performance-oriented management. This study develops a system-level analytical framework to examine future-proofing as an emergent outcome of interactions among institutional and contextual drivers, planning mechanisms, innovation, and design capabilities. The empirical analysis is conducted using data collected from professionals engaged in hospital infrastructure projects in Iraq. A Partial Least Squares Structural Equation Modeling (PLS-SEM) approach is employed to evaluate both direct and indirect relationships within the proposed system model. The results demonstrate that institutional and contextual drivers significantly influence planning mechanisms, which in turn act as a central structuring layer affecting both innovation and design capabilities. Innovation does not exhibit a statistically significant direct effect on long-term system adaptability, indicating that technological advancement alone is insufficient to ensure sustained performance. In contrast, design capabilities constitute the primary determinant of future-proofing, with a strong mediating effect on lifecycle system performance. The findings provide important implications for engineering management by emphasizing that long-term adaptability in hospital infrastructure systems depends on the alignment between planning structures and implementation-oriented design capabilities, rather than on innovation intensity alone.

**Keywords:** Hospital infrastructure systems; System performance; Future-proofing; Lifecycle adaptability; Design capabilities; Planning mechanisms; Partial Least Squares Structural Equation Modeling

## 1 Introduction

Hospitals represent highly complex infrastructure systems because their long-term performance depends on the interaction of organizational arrangements, clinical processes, technical systems, and the wider operational environment in which care is delivered [1, 2]. In institutionally unstable settings, this complexity becomes harder to manage, as health system resilience is frequently challenged by governance fragmentation, conflict-related disruption, and weak continuity across planning and service delivery processes [3, 4]. Unlike conventional infrastructure assets, hospitals must maintain performance over extended life cycles while accommodating continuing shifts in models of care, medical technologies, safety expectations, and patterns of demand [2, 5]. This makes adaptability, flexibility, and system coordination central design concerns rather than secondary operational issues [2, 5].

Recent hospital design research increasingly argues that the major risk is not only physical deterioration, but also the inability of facilities to remain functionally and operationally aligned with evolving healthcare requirements. In

this sense, obsolescence is closely linked to insufficient adaptability and weak anticipation of change during planning and design [6, 7]. This problem is reinforced by the fact that hospital performance is strongly shaped by early front-end decisions, while healthcare facility evaluation research continues to show the importance of predesign evaluation, post-occupancy evaluation, and evidence-based feedback in improving long-term building performance [2, 8]. In response, the concept of future-proofing has gained increased attention in hospital building research as a proactive approach aimed at embedding flexibility, adaptability, and lifecycle thinking into early decision-making so that facilities can better accommodate uncertainty and change over time [6, 7].

Within the context of hospital infrastructure systems, future-proofing is frequently linked to innovation, especially digital and technological innovation, including smart hospital systems, interoperability, and data-enabled operational infrastructures [9, 10]. However, current research increasingly suggests that innovation on its own does not automatically secure long-term operational resilience or future-ready performance unless it is supported by coherent planning and implementation structures [11, 12]. In parallel, hospital design research has emphasized that long-term performance depends not only on technological advancement but also on how early planning decisions are translated into workable spatial and operational configurations. Recent design studies therefore stress the role of integrated planning, simulation-informed evaluation, and performance-oriented design support in reducing downstream dysfunction and improving adaptability in healthcare facilities [13, 14].

This perspective challenges the linear assumption that innovation directly leads to future-proofing. Instead, it suggests that planning practices and design capabilities operate as critical mediating mechanisms through which strategic intentions are converted into adaptable and operationally robust hospital environments [6, 13]. This issue becomes even more important in institutionally unstable settings, where fragmented implementation conditions can weaken the translation of innovation into actual long-term building performance [3, 4, 15]. Accordingly, the novelty of the present study does not lie in introducing entirely new constructs. Rather, it lies in examining the systemic configuration of relationships among institutional and contextual drivers, planning practices, innovation, design capabilities, and future-proofing within an institutionally unstable hospital context.

Against this backdrop, the present study analyzes future-proofing in hospital infrastructure systems as the outcome of an interdependent system, focusing on the relationships among institutional and contextual drivers, planning practices, innovation, and design capabilities in Iraq. Using Partial Least Squares Structural Equation Modeling (PLS-SEM), the study aims to clarify the pathways through which long-term functional and operational performance can be better sustained in hospital infrastructure systems [16, 17].

## **2 Literature Review and Conceptual Framework Development**

### **2.1 Hospitals as Complex Socio-Technical Systems and the Problem of Obsolescence**

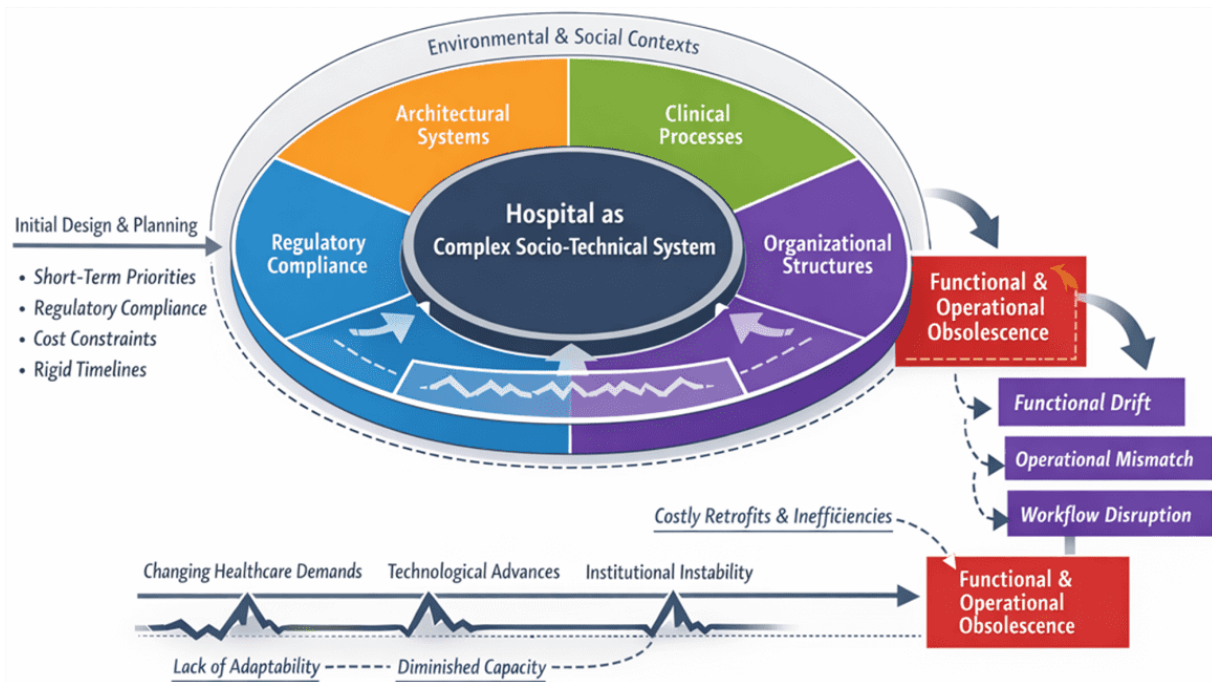
Recent scholarship increasingly conceptualizes hospitals not merely as physical facilities, but as complex socio-technical systems characterized by layered interdependencies among spatial configuration, clinical processes, technological infrastructures, governance structures, and patterns of use [2, 17]. Within this perspective, spatial performance cannot be separated from operational and organizational performance without weakening overall system effectiveness. Figure 1 illustrates the hospital as a complex socio-technical system and shows how functional and operational obsolescence emerges through the interaction of clinical, organizational, regulatory, and architectural subsystems under changing contextual conditions.

Unlike conventional infrastructure assets, hospitals operate under conditions of continuing clinical evolution, technological change, regulatory pressure, and shifting patient demand. Accordingly, their performance must be evaluated in terms of long-term adaptability and functional responsiveness rather than structural durability alone [2, 6].

A growing body of literature indicates that one of the most significant risks facing hospital facilities is functional and operational obsolescence rather than simple material deterioration [6, 8]. Obsolescence emerges when spatial layouts, infrastructure systems, and organizational logics no longer support evolving healthcare delivery models even though the facility may remain physically intact. Post-occupancy and healthcare facility evaluation studies repeatedly identify workflow inefficiencies, limited adaptability, and the need for costly modifications after occupation as recurring indicators of this condition [8, 18].

From a complex systems perspective, such obsolescence can be understood as a failure of adaptive capacity embedded in early planning assumptions and system configuration decisions [6, 17]. When hospital projects are shaped by rigid standards, fixed functional programs, and short-term compliance priorities, the capacity for long-term change becomes structurally constrained [6, 19].

The literature therefore supports a systemic interpretation of hospital obsolescence: it is not an isolated structural deficiency, but an emergent outcome of misaligned planning, constrained adaptability, and weak alignment between spatial, operational, and organizational requirements over time [2, 6, 8]. This framing provides the conceptual basis for examining future-proofing not as a single design feature, but as a relational and system-dependent outcome.



**Figure 1.** The hospital as a complex socio-technical system and the emergence of obsolescence as adaptive failure over time

Source: Based on the reference [2, 6, 8, 17]

## 2.2 Institutional and Contextual Drivers in Hospital Infrastructure Systems

Institutional and contextual drivers—including regulatory regimes, health policy frameworks, governance arrangements, financing structures, technological trajectories, and environmental pressures—play a decisive role in shaping hospital infrastructure planning and long-term system performance [4, 12, 20–23]. Rather than functioning as passive background conditions, these drivers influence how planning priorities are defined, how resources are allocated, and how adaptability is either enabled or constrained over time [12, 21].

In institutionally stable settings, integrated governance structures, policy continuity, and long-term capital planning can support cumulative learning and lifecycle-oriented decision-making [20, 21]. By contrast, in institutionally volatile or fragile environments, planning cycles are often fragmented, reactive, and shaped by short-term pressures, which weakens the incorporation of flexibility and future-oriented capacity into hospital infrastructure systems [4, 24]. Under such conditions, projects tend to prioritize immediate delivery, emergency response, and procedural compliance over systemic adaptability and long-term operational robustness [4, 24].

Emerging studies on health systems resilience, future hospitals, and climate-resilient healthcare infrastructure further suggest that institutional discontinuity constrains the embedding of flexible infrastructures, scenario-based planning, and adaptive decision frameworks [10, 22, 25]. At the same time, technological change and sustainability imperatives are adding new pressures to hospital planning by requiring infrastructures that can accommodate digital integration, evolving service models, and environmental performance targets [10, 17, 26].

Accordingly, the literature indicates that institutional and contextual drivers should not be treated merely as external background variables. Instead, they actively configure planning logic and shape long-term adaptive outcomes in hospital infrastructure systems [12, 21, 23]. This insight supports their treatment in the present study as structural antecedents within the proposed conceptual model.

As summarized in Table 1, institutional and contextual drivers shape hospital infrastructure planning through regulatory, governance, financial, technological, environmental, and temporal conditions that influence long-term adaptability and system performance.

## 2.3 Planning Practices as a Strategic Mediator

Contemporary research increasingly distinguishes between reactive planning, which is oriented toward immediate operational and delivery pressures, and proactive planning, which incorporates systems thinking, long-term coordination, learning, and adaptability into decision-making [8, 27]. In hospital infrastructure systems, this distinction is especially important because planning does not merely schedule implementation; it mediates how institutional priorities are translated into spatial, technological, and operational configurations over time [12, 22].

**Table 1.** Key institutional and contextual drivers influencing hospital infrastructure planning

No.	Driver Category	Description
1	Regulatory frameworks	Encompass laws, regulations, accreditation requirements, and safety standards that impose design constraints and shape the functional and infrastructural configuration of hospital systems. These frameworks strongly influence early design decisions and compliance priorities [12, 21].
2	Health policies	Represent national or regional health strategies that define care models, service capacity, and development priorities, thereby influencing planning horizons and system organization patterns in hospital infrastructure planning [10, 12].
3	Governance models	Relate to decision-making structures, degrees of centralization or decentralization, and coordination mechanisms among actors, which determine whether planning processes become integrated and adaptive or rigid and fragmented [4, 21].
4	Funding mechanisms	Include financing sources, budget allocation procedures, and cost-control logics, which frequently favor short-term delivery priorities over long-term flexibility and lifecycle performance [23, 24].
5	Technological trajectories	Reflect the pace of change in medical, digital, and data-enabled technologies and the corresponding need for infrastructural readiness, interoperability, and future integration capacity [10, 17].
6	Environmental pressures	Include climate-related risks, sustainability targets, and broader environmental performance requirements that affect infrastructure configuration, building operation, and long-term resilience planning [25, 26].
7	Temporal constraints	Refer to pressures for accelerated delivery, emergency response, and post-crisis reconstruction, often compressing planning phases and reducing opportunities for strategic foresight [4, 24].
8	Institutional stability	Reflect the degree of policy continuity, institutional memory, and cumulative organizational learning, which shape the capacity for long-term planning and reduce repeated configuration errors in hospital projects [21, 22].

Source: Based on the reference [4, 10, 12, 17, 21–26]

Empirical studies further suggest that long-term planning horizon, stakeholder integration, and performance-oriented design support significantly affect the extent to which adaptability can be embedded in healthcare projects [13, 22, 28]. By contrast, fragmented planning often produces spatial rigidity, weak interoperability, and innovation initiatives that remain operationally isolated or underutilized [9, 10, 27].

Several recent studies also indicate that the value of innovation is highly contingent on planning coherence and implementation capacity. When technological or organizational innovation is introduced within weak planning frameworks, its contribution to long-term resilience and future readiness is often limited [11, 12, 17]. Taken together, planning practices can be understood as a mediating layer through which institutional and contextual pressures are translated into system-level and technological decisions. This positions planning as a structural pivot within the conceptual model.

#### 2.4 Innovation in Hospital Infrastructure Systems: Opportunities and Constraints

Earlier and continuing work on hospital transformation often presents innovation—particularly digital infrastructure, interoperability, automation, and smart hospital systems—as an important enabler of improved coordination, responsiveness, and system modernization [9, 10, 17]. From this perspective, technological advancement can strengthen hospital resilience by enhancing information flow, integration capacity, and operational visibility across the care environment.

However, more recent empirical research challenges a simple linear view in which innovation directly produces future-proofing. Studies increasingly show that technological innovation alone does not necessarily reduce obsolescence when spatial systems remain inflexible, interoperability is weak, or institutional integration is insufficient [6, 22, 27]. In some cases, innovation may even increase system complexity without generating corresponding gains in adaptive capacity if planning and implementation conditions are not aligned [11, 12, 17].

The literature therefore supports two competing interpretations. The first treats innovation as a direct enabler of future-proofing through digital transformation and smart infrastructure integration [9, 17]. The second treats innovation as a contingent factor whose long-term value depends on planning coherence, institutional support, and implementation capacity [11, 12, 22]. This divergence provides a clear basis for empirically testing the non-direct role of innovation within the structural model adopted in this study.

## 2.5 Design Capabilities as an Implementation Mechanism

Design capabilities refer to the implementation-oriented properties embedded in spatial configuration, structural systems, service distribution, and the capacity of the building to accommodate functional and technical change over time. In hospital infrastructure systems, these capabilities typically include flexibility, adaptability, maintainability, modularity, and upgrade potential [6, 7, 20]. In this sense, design capabilities operate at the execution level by shaping whether strategic intentions can be materially translated into a built environment capable of absorbing change during operation.

Unlike innovation, which may remain conceptual or technologically isolated, design capabilities are expressed through the physical and infrastructural characteristics of the facility itself. Recent hospital design research shows that adaptable layouts, modular approaches, and open-ended system strategies can improve lifecycle performance and support future functional transformation with lower disruption costs [6, 7, 29]. Accordingly, the literature consistently positions design capabilities as the implementation mechanism through which planning priorities and innovation strategies become spatially and operationally materialized in hospital projects.

## 2.6 Future-Proofing as a Systemic Outcome

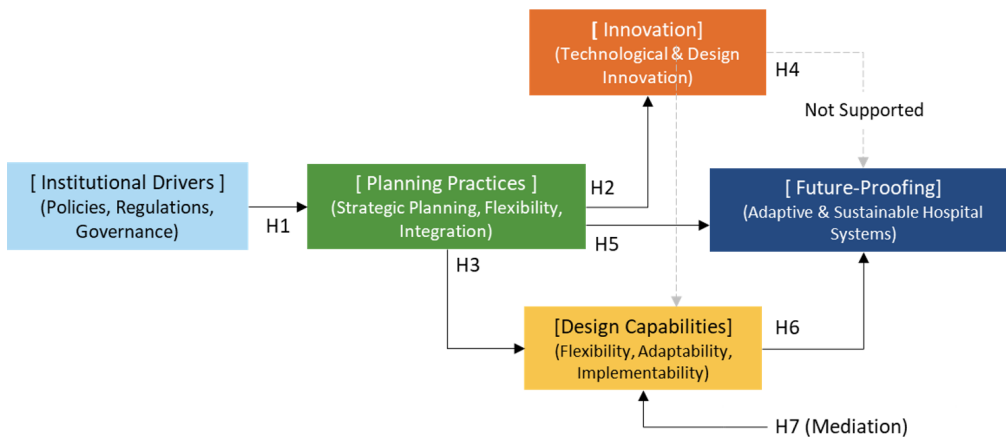
Future-proofing has increasingly evolved from a narrow technical notion into a broader system-level strategy that emphasizes lifecycle thinking, resilience, adaptability, and anticipatory decision-making in hospital building design [6, 22, 30]. Rather than referring to a single technical feature, the concept is now understood as a proactive orientation that seeks to prepare hospital infrastructure for evolving clinical practices, technological transitions, organizational change, and uncertain future conditions.

Despite this growing conceptual clarity, empirical evidence remains comparatively fragmented regarding the causal configuration through which future-proofing is achieved. Existing studies frequently discuss flexibility, modularity, resilience, or digital transformation as important ingredients, but fewer studies examine how institutional drivers, planning practices, innovation, and design capabilities interact within one integrated explanatory structure, especially in institutionally unstable contexts [4, 22, 30].

The literature therefore suggests that future-proofing should be understood not as the automatic outcome of innovation, nor solely as a planning device, but as an emergent result of systemic interaction among governance conditions, planning coherence, implementation capacity, and the adaptive properties of the built system itself [6, 22, 30]. This interpretation supports the present study's treatment of future-proofing as the outcome variable in the proposed model.

## 2.7 Conceptual Framework Development

Based on the foregoing review, this study develops a conceptual framework that treats future-proofing in hospital infrastructure systems as the emergent outcome of interaction among four principal constructs: institutional and contextual drivers, planning practices, innovation, and design capabilities. Within this structure, institutional and contextual drivers operate as antecedent conditions shaping the logic of planning; planning practices function as the central mediating layer through which strategic priorities are translated into coordinated decisions; innovation operates as a conditional mechanism whose contribution depends on planning coherence and implementation conditions; and design capabilities act as the operational implementation layer through which long-term adaptability is materially embedded in the hospital system [12, 22, 30].



**Figure 2.** Conceptual framework of future-proofing in hospital infrastructure systems

Source: Based on the reference [6, 12, 22, 30]

Figure 2 illustrates the proposed conceptual framework linking institutional and contextual drivers, planning practices, innovation, design capabilities, and future-proofing in hospital infrastructure systems.

Taken together, the reviewed literature indicates that institutional drivers, planning practices, innovation, and design capabilities have each been examined as important dimensions of hospital adaptability and future-proofing. However, much of this scholarship addresses these dimensions separately or in partial combinations rather than as interdependent elements within a single explanatory structure. As a result, limited empirical evidence is available on how their structural relationships operate in institutionally unstable healthcare contexts, where governance volatility, implementation constraints, and fragmented planning conditions may significantly reshape long-term adaptive performance [4, 24, 30]. This gap provides the rationale for the present study and supports the relevance of the proposed conceptual framework.

This framework shifts the focus from innovation-centric explanations toward capability-based systemic performance.

### 3 Research Hypotheses

Drawing on the literature that conceptualizes hospitals as highly complex socio-technical systems, within which planning decisions are intertwined with operations, governance, system configuration, and digital infrastructure over time, this study formulates its hypotheses to examine the causal mechanisms through which future-proofing emerges as a systemic outcome rather than the result of a single variable [18, 22]. Within this logic, future-proofing is assumed to depend on the system's capacity for responsiveness and adaptability, which is practically associated with the robustness of planning, the nature of innovation, and the extent to which design capabilities enable the translation of strategic intentions into solutions that can be absorbed operationally over time [22, 29].

#### 3.1 Institutional and Contextual Drivers and Planning Practices

The literature emphasizes that hospital infrastructure planning does not take place within an isolated design domain. Rather, it is embedded within a broader institutional system that includes funding structures, governance arrangements, regulatory requirements, decision-making chains, and policy continuity or volatility. These factors directly influence the planning horizon and its orientation, whether proactive or reactive, as well as the extent to which operational considerations are integrated at early stages [21, 27]. Recent studies on health system resilience further indicate that responsiveness and adaptability are often constrained by institutional pressures that produce short-term planning decisions and fragmented implementation conditions [4, 24].

H1: Institutional and contextual drivers have a positive and statistically significant effect on planning practices in hospital infrastructure systems.

#### 3.2 Planning Practices and Innovation

Contemporary literature indicates that innovation in hospital environments, whether digital, operational, or system-related, does not readily generate operational value unless it is embedded within planning practices capable of managing uncertainty and linking strategic decisions to realistic implementation and operational scenarios [13, 17]. Studies addressing healthcare system readiness for change further suggest that innovation may become burdensome when introduced through reactive planning logics or under fragmented institutional conditions that produce isolated and non-scalable solutions [11, 24].

H2: Planning practices have a positive and statistically significant effect on innovation in hospital infrastructure systems.

#### 3.3 Planning Practices and Design Capabilities

Recent literature distinguishes between the existence of a theoretical intention toward flexibility and the realization of actual design capabilities, such as changeability, maintainability, spatial flexibility, and transition capacity. Design capabilities are therefore conceptualized as implementation-oriented outcomes that depend on early planning decisions related to infrastructure, system configuration, and the enabling conditions for change over time [6, 20, 29]. In parallel, evaluation and decision-support studies in healthcare architecture indicate that flexibility-related attributes are developed through layered planning decisions rather than through retrospective or add-on interventions [13, 28].

H3: Planning practices have a positive and statistically significant effect on design capabilities in hospital infrastructure systems.

#### 3.4 Innovation and Future-Proofing

Despite the widespread association between innovation and future-proofing, recent literature suggests that this relationship is not always linear. Studies on hospital resilience and healthcare transformation indicate that the introduction of new technologies or service models may increase system complexity and multiply points of failure if they are not translated into adaptable operational and spatial structures [11, 17]. Recent debates in complex systems

and engineering management literature further challenge the assumption that innovation operates as an autonomous driver of long-term adaptability [18, 22]. Instead, innovation is increasingly conceptualized as a contingent mechanism whose effectiveness depends on institutional coherence, lifecycle integration, and implementation capacity. Within complex socio-technical systems, technological advancement alone does not necessarily generate anticipatory capacity unless embedded within structured planning and operational alignment [22, 30].

H4: Innovation does not have a direct and statistically significant effect on future-proofing in hospital infrastructure systems.

### **3.5 Planning Practices and Future-Proofing**

Recent literature emphasizes that proactive planning enhances healthcare facilities' capacity to respond to change by embedding the logic of long-term operational fit and by addressing issues of expansion, modification, and reconfiguration at early stages [6, 22]. Contemporary studies on building adaptability further indicate that long-term performance is closely associated with planning decisions that determine whether a system can accommodate future transformation without major functional disruption [20, 29].

H5: Planning practices have a positive and statistically significant effect on future-proofing in hospital infrastructure systems.

### **3.6 Design Capabilities and Future-Proofing**

The literature on healthcare facility adaptability indicates that future-proofing is practically manifested through capabilities such as flexibility, changeability, maintainability, and the management of disruption during modification processes. These attributes are directly associated with enabling adaptation without compromising system performance [7, 29, 30]. Reviews on building adaptability further support the view that the capacity for modification and reconfiguration constitutes a central condition of long-term operational sustainability in infrastructure systems [20].

H6: Design capabilities have a positive and statistically significant effect on future-proofing in hospital infrastructure systems.

### **3.7 The Mediating Role of Design Capabilities**

From a systems perspective, sound planning at the strategic level is insufficient unless it is translated into implementable system attributes that can be operationalized during use. The literature on resilience, future-proofing, and healthcare adaptability indicates that a critical gap often emerges when planning decisions remain conceptual and are not converted into operational design solutions capable of absorbing the effects of change over time [6, 22, 30]. Accordingly, design capabilities are assumed to function as a mediating mechanism through which the influence of planning practices is transmitted to future-proofing outcomes.

H7: Design capabilities mediate the relationship between planning practices and future-proofing in hospital infrastructure systems.

## **4 Research Methodology**

### **4.1 Research Design and Methodological Approach**

This study adopts a system-oriented analytical approach to examine future-proofing in hospital infrastructure systems as the outcome of interrelated institutional conditions, planning practices, innovation processes, and implementation-oriented design capabilities. The methodological premise of the study is that long-term adaptive performance in healthcare infrastructure does not emerge from a single factor; rather, it results from the interaction of multiple latent dimensions operating within a complex and institutionally unstable context [17, 21, 29].

Given the multidimensional and relational nature of these constructs, PLS-SEM was selected as the most appropriate analytical technique. PLS-SEM is widely used when the objective is theory development, prediction, and the examination of causal relationships among latent variables measured through perceptual indicators, particularly in applied and context-sensitive research settings [30–33].

### **4.2 Study Context and Sample**

The empirical study was conducted within the Iraqi healthcare context, which represents a relevant setting for examining future-proofing under conditions of institutional instability, policy volatility, and accelerated reconstruction. In such contexts, hospital infrastructure systems are often exposed to functional and operational misalignment due to discontinuities between planning assumptions and long-term operational realities [3, 4, 15].

Data were collected from professionals directly involved in the planning, design, and implementation of hospital projects, including architects, planners, engineers, and project-level decision-makers. Respondents were selected on the basis of professional experience and direct engagement in hospital projects, in line with recommendations emphasizing the value of expert-based knowledge in complex socio-technical environments [17, 20].

To ensure methodological adequacy, the sample size was assessed against established PLS-SEM guidelines. According to the widely cited 10-times rule, the minimum sample should be at least ten times the maximum number of structural paths directed at any endogenous construct [31, 33]. In the present model, the maximum number of incoming paths is three, implying a minimum threshold of 30 observations. The achieved sample size of 100 therefore exceeds this requirement. In addition, contemporary guidance suggests that this sample size is adequate for detecting medium effects in models of comparable complexity, particularly when explanatory power is acceptable [30, 31].

### 4.3 Measurement Instrument and Operationalization of Variables

To operationalize the theoretical constructs identified in the literature review, a structured questionnaire was developed using indicators derived from prior studies on hospital infrastructure systems, planning, innovation, adaptability, and future-proofing. These indicators were contextually adapted to the Iraqi healthcare environment while preserving their conceptual intent and analytical relevance [6, 21, 30]. Five latent variables were included in the model:

- **Institutional and contextual drivers**, representing external determinants that influence planning priorities and strategic orientations in hospital infrastructure systems [12].
- **Planning practices**, reflecting planning horizons, decision patterns, stakeholder coordination, and institutional integration [26].
- **Innovation, representing conceptual**, technological, and organizational innovation in hospital infrastructure systems [9, 16].
- **Design capabilities**, representing implementation-oriented capacities such as maintainability, flexibility, changeability, and transition potential [28, 29].
- **Future-proofing**, conceptualized in this study as anticipatory adaptive capacity embedded in hospital infrastructure systems. Unlike realized operational performance, this construct captures proactive design provisions that support long-term technological integration, functional reconfiguration, lifecycle evolution, and uncertain healthcare scenarios [6, 21, 29].

**Table 2.** Latent variables and measurement indicators used in the study

Code	Latent Variable	Indicator	Indicator Description
A	Institutional and contextual drivers	A1	Industrial and technological drivers influencing hospital infrastructure-systems
		A2	Digital drivers and technological transformation in the healthcare-sector
		A3	Regulatory and institutional drivers (laws, governance, policies)
		A4	Environmental and sustainability-related drivers
		A5	Time-related drivers associated with crises and rapid change
B	Planning practices	B1	Long-term planning horizon
		B2	Planning mode (reactive vs. proactive)
		B3	Planning orientation (operational vs. strategic)
		B4	Patterns of stakeholder interaction
		B5	Level of institutional integration in planning
C	Innovation	C1	Innovation in system concepts
		C2	Technological and digital innovation
		C3	Process and managerial innovation
		C4	Innovation in system operation and user interaction
D	Design capabilities	D1	Maintainability
		D2	Functional and structural flexibility
		D3	Changeability and reconfiguration capacity
		D4	Capacity to mitigate operational disruption
		D5	Capacity for incremental improvement and upgrading
		D6	Capacity for future transition and expansion
Y	Future-proofing	Y1	Embedded system adaptability anticipating future functional change
		Y2	Design provisions enabling long-term technological integration
		Y3	Lifecycle-oriented planning embedded in system configuration
		Y4	Capacity to accommodate uncertain future healthcare scenarios

Source: Based on the reviewed literature [6, 9, 12, 16, 21, 26, 28–30]

All indicators were measured using a five-point Likert scale, which remains widely used in built environment and professional perception research. Table 2 presents the latent variables and their corresponding indicators adopted in

the study.

The measurement items were primarily derived from previously validated constructs and then refined to reflect local institutional conditions. No entirely new theoretical constructs were introduced; instead, established measures were adapted for contextual relevance and clarity.

#### **4.4 Data Collection Procedures**

The questionnaire was distributed to a targeted sample of professionals involved in hospital projects across different Iraqi regions. Data collection was conducted online between January 2025 and March 2025. Participation was voluntary, and responses were collected anonymously. Before full deployment, the questionnaire was reviewed to improve wording clarity and conceptual alignment between the indicators and the underlying constructs, thereby strengthening face validity and content validity [30, 34].

The collected responses were subsequently screened for completeness and consistency before statistical analysis. This step was undertaken to ensure data quality and reduce the risk of biased estimation arising from incomplete or inconsistent records.

#### **4.5 Data Analysis Technique**

Data were analyzed using PLS-SEM in two main stages. The first stage focused on the assessment of the measurement model in terms of reliability and validity, while the second stage examined the structural model and the proposed hypotheses. Bootstrapping was employed to estimate the statistical significance of path coefficients, given its suitability for medium-sized samples and for data that may deviate from normality assumptions [30, 31, 33].

This analytical procedure enabled the examination of both direct and indirect effects among the study variables, including the mediating role of design capabilities in explaining future-proofing outcomes in hospital infrastructure systems.

#### **4.6 Measurement Model Assessment**

The measurement model was assessed prior to hypothesis testing to verify indicator reliability and construct validity. This assessment included four components. First, internal consistency reliability was examined using Cronbach's alpha and composite reliability, following threshold values commonly adopted in contemporary PLS-SEM research [30, 31]. Second, convergent validity was evaluated using the Average Variance Extracted (AVE) to confirm that the indicators adequately captured their respective constructs [30, 33]. Third, discriminant validity was assessed using the Fornell–Larcker criterion and the Heterotrait–Monotrait (HTMT) ratio to ensure conceptual distinctiveness among the latent variables [32, 35].

This assessment ensured that the relationships tested in the structural model reflected substantive theoretical associations rather than measurement artifacts arising from inadequate construct quality.

#### **4.7 Structural Model Assessment**

After establishing the adequacy of the measurement model, the structural model was evaluated through path coefficients, coefficients of determination ( $R^2$ ), effect sizes ( $f^2$ ), and bootstrapped significance levels. A large number of bootstrap resamples was used to strengthen the robustness of statistical inference under non-normality assumptions and applied research conditions [30, 31, 33].

Particular attention was given to the mediating role of design capabilities in the relationship between planning practices and future-proofing, in line with the conceptual assumption that future-proofing is not achieved through planning alone, but through implementation mechanisms that can be activated and sustained during operation.

#### **4.8 Methodological Considerations and Reliability**

Several supporting procedures were adopted to improve methodological reliability. The indicators were reviewed linguistically and conceptually before distribution in order to reduce ambiguity and misinterpretation. In addition, the questionnaire design sought to minimize common method bias by separating indicators across constructs and avoiding unnecessary overlap in wording, which is consistent with recommended practices in Structural Equation Modeling (SEM) research [36]. Data analysis was conducted using SmartPLS 4 [37]. Taken together, these procedures enhance confidence that the observed relationships reflect meaningful patterns in hospital infrastructure planning and future-proofing rather than incidental statistical associations.

## 5 Results

### 5.1 Measurement Model Assessment

Prior to testing the causal relationships in the structural model, the measurement model was evaluated to assess the reliability and validity of the measurement indicators, following established PLS-SEM procedures [30, 31].

The analysis results indicated that all outer loadings exceeded the minimum acceptable threshold of 0.70. This suggests that the indicators were strongly associated with their respective latent constructs and that indicator reliability was satisfactory for model estimation [30, 31].

Internal consistency reliability was further examined using Cronbach's Alpha and Composite Reliability. All values exceeded the recommended threshold of 0.70, indicating adequate internal consistency among the indicators used to measure each latent construct [30, 31].

Convergent validity was assessed using the AVE. All AVE values were above the minimum acceptable level of 0.50, indicating that each construct explained a sufficient proportion of variance in its corresponding indicators and thus demonstrated acceptable convergent validity [30, 35].

As shown in Table 3, all constructs achieved acceptable levels of internal consistency reliability and convergent validity. The corresponding graphical outputs are presented in Figure 3 and Figure 4. Figure 3 presents the AVE values for the latent constructs, illustrating the extent to which each construct explains the variance of its associated indicators. Figure 4 displays the corresponding reliability measures, providing a visual summary of the internal consistency of the measurement model across the examined constructs. Together, these graphical outputs support the adequacy of the measurement model and reinforce the validity of proceeding to structural model evaluation.

**Table 3.** Latent variables and measurement indicators used in the study

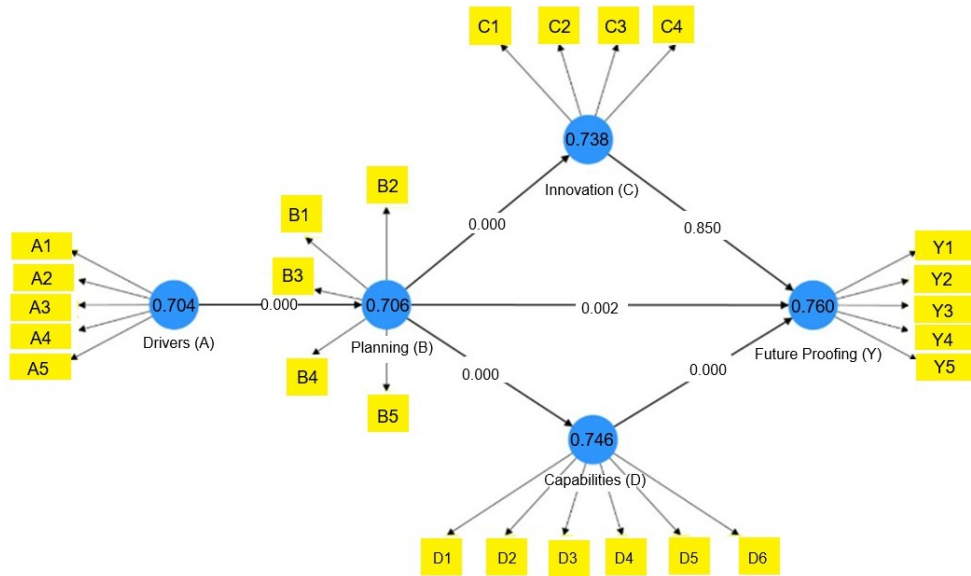
Construct	Indicator	Outer Loading	Cronbach's Alpha	Composite Reliability (CR)	Average Variance Extracted (AVE)
Drivers (A)	A1	0.78	0.84	0.89	0.62
	A2	0.81			
	A3	0.79			
	A4	0.76			
	A5	0.80			
Planning (B)	B1	0.82	0.86	0.91	0.67
	B2	0.84			
	B3	0.79			
	B4	0.81			
	B5	0.83			
Innovation (C)	C1	0.77	0.80	0.87	0.63
	C2	0.81			
	C3	0.79			
	C4	0.82			
Capabilities (D)	D1	0.84	0.88	0.92	0.65
	D2	0.81			
	D3	0.79			
	D4	0.83			
	D5	0.80			
	D6	0.78			
Future-proofing (Y)	Y1	0.85	0.90	0.93	0.71
	Y2	0.83			
	Y3	0.86			
	Y4	0.82			

Source: Generated from the survey data using SmartPLS 4

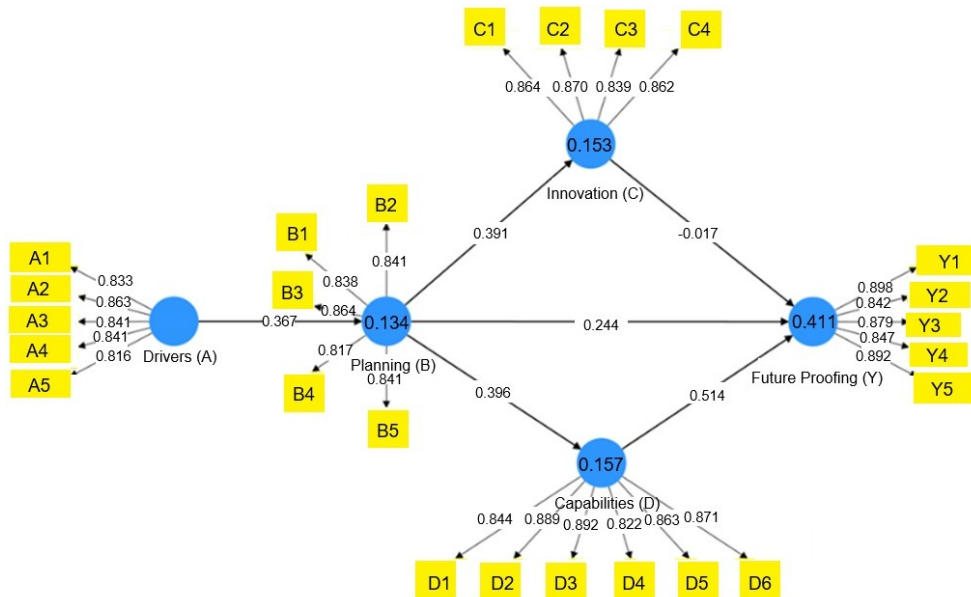
### 5.2 Discriminant Validity

To ensure the conceptual distinctiveness of the latent variables and to avoid unjustified construct overlap, discriminant validity was assessed using the HTMT ratio, which is widely recommended in contemporary PLS-SEM research [32].

All HTMT values were below the conservative threshold of 0.85, confirming satisfactory discriminant validity among the examined constructs. Table 4 presents the HTMT matrix.



**Figure 3.** Convergent validity assessment via Average Variance Extracted (AVE) for each latent variable (SmartPLS output)



**Figure 4.** Structural model with path coefficients and explained variance ( $R^2$ )

Source: Generated from the survey data using SmartPLS 4

**Table 4.** Discriminant validity assessment using the Heterotrait–Monotrait (HTMT) criterion

Constructs	Drivers	Planning	Innovation	Capabilities	Future-Proofing
Drivers	-	-	-	-	-
Planning	0.367	-	-	-	-
Innovation	0.255	0.391	-	-	-
Capabilities	0.463	0.396	0.506	-	-
Future-proofing	0.387	0.441	0.338	0.602	-

Source: Generated from the survey data using SmartPLS 4

Cross-loadings were also examined to provide additional verification. Each indicator loaded higher on its associated construct than on the remaining constructs, further supporting the adequacy of conceptual discrimination among the latent variables [30, 32].

Collectively, these results confirm that the constructs are empirically distinct and represent independent conceptual dimensions within the proposed future-proofing model for hospital infrastructure systems.

### 5.3 Structural Model Assessment and Hypothesis Testing

Following confirmation of the adequacy and validity of the measurement model, the analysis proceeded to the evaluation of the structural model in order to test the research hypotheses and examine the causal relationships among the latent variables. This stage involved the assessment of path coefficients and their statistical significance using the bootstrapping procedure, as well as the evaluation of the coefficients of determination ( $R^2$ ), in accordance with established methodological procedures in PLS-SEM research [30, 31, 33].

Figure 4 illustrates the final structural model obtained from the PLS-SEM analysis, presenting the estimated path coefficients, the coefficients of determination ( $R^2$ ) for the endogenous constructs, and the indicator loadings after model estimation. In addition, Table 5 reports the path coefficients, significance levels, and the results of hypothesis testing.

**Table 5.** Structural model results and hypothesis testing

Hypothesis	Path	$\beta$	$t$ -Value	$p$ -Value	Result
H1	Drivers $\rightarrow$ Planning	0.367	4.585	0.000	Supported
H2	Planning $\rightarrow$ Innovation	0.391	4.287	0.000	Supported
H3	Planning $\rightarrow$ Capabilities	0.396	4.174	0.000	Supported
H4	Innovation $\rightarrow$ Future-proofing	-0.017	0.189	0.850	Not supported
H5	Planning Future-proofing	0.244	3.064	0.002	Supported
H6	Capabilities $\rightarrow$ Future-proofing	0.514	6.163	0.000	Supported

Source: Generated from the survey data using SmartPLS 4

#### 5.3.1 Effect of institutional and contextual drivers on planning practices

The results reveal a positive and statistically significant effect of institutional and contextual drivers on planning practices ( $\beta = 0.367$ ,  $t = 4.585$ ,  $p < 0.001$ ), thus supporting Hypothesis H1. The corresponding effect size ( $f^2 = 0.186$ ) indicates a moderate explanatory contribution of institutional and contextual drivers to planning practices. These findings suggest that regulatory frameworks, policy pressures, and time- and finance-related constraints play an important role in shaping planning decisions in hospital projects, particularly within institutionally unstable contexts.

#### 5.3.2 Effect of planning practices on innovation and design capabilities

The results further show a positive and statistically significant effect of planning practices on both innovation and design capabilities, thus supporting Hypotheses H2 and H3. Specifically, planning practices have a significant effect on innovation ( $\beta = 0.391$ ,  $t = 4.287$ ,  $p < 0.001$ ,  $f^2 = 0.155$ ) and on design capabilities ( $\beta = 0.396$ ,  $t = 4.174$ ,  $p < 0.001$ ,  $f^2 = 0.180$ ). The slightly stronger effect on design capabilities suggests that planning contributes more directly to implementation-oriented capacity than to innovation alone. Taken together, these findings suggest that planning operates as a key mediating layer through which broader institutional conditions are translated into both innovation processes and executable design capabilities.

#### 5.3.3 Innovation and future-proofing

In contrast, innovation did not show a direct and statistically significant effect on future-proofing ( $\beta = 0.017$ ,  $t = 0.189$ ,  $p < 0.850$ ,  $f^2 = 0.000$ ). The negligible path coefficient and zero effect size suggest that innovation alone has limited explanatory relevance for future-proofing in the examined context. This finding implies that innovation may not translate into improved long-term operational performance or reduced functional obsolescence unless it is supported by coherent planning and implementation-oriented design capabilities.

#### 5.3.4 Planning practices and design capabilities as direct determinants of future-proofing

The results indicate a positive and statistically significant direct effect of planning practices on future-proofing ( $\beta = 0.244$ ,  $t = 3.064$ ,  $p = 0.002$ ,  $f^2 = 0.080$ ), thereby supporting Hypothesis H5. Although the corresponding effect size is relatively small, it suggests that planning makes a meaningful direct contribution to future-proofing.

In addition, design capabilities represent the strongest direct predictor of future-proofing ( $\beta = 0.514$ ,  $t = 6.163$ ,  $p < 0.001$ ,  $f^2 = 0.3102$ ). The comparatively larger path coefficient and effect size suggest that flexibility, changeability, transition capacity, and provision for future expansion function as the most influential implementation-oriented mechanisms for reducing obsolescence and supporting long-term operational continuity in hospital facilities.

### 5.3.5 The mediating role of design capabilities

Finally, the results of the indirect effects analysis indicate that design capabilities mediate the relationship between planning practices and future-proofing, thereby supporting Hypothesis H7. This interpretation is reinforced by the statistically significant effect of planning practices on design capabilities ( $\beta = 0.396, p < 0.001$ ) and the strong direct effect of design capabilities on future-proofing ( $\beta = 0.514, p < 0.001$ ). Taken together, these findings suggest that a substantial part of the influence of planning practices on future-proofing is transmitted through their translation into actionable design capabilities.

### 5.3.6 Explanatory power of the structural model

To assess the explanatory power of the structural model, the coefficients of determination ( $R^2$ ) for the endogenous constructs were examined. The results indicate that the model explains 13.4% of the variance in planning practices ( $R^2 = 0.134$ ), 15.3% of the variance in innovation ( $R^2 = 0.153$ ), 15.7% of the variance in design capabilities ( $R^2 = 0.157$ ), and 41.1% of the variance in future-proofing ( $R^2 = 0.411$ ). Among these, the explanatory power for future-proofing is the strongest, indicating that the proposed model has moderate explanatory capability in accounting for long-term system adaptability in hospital infrastructure systems.

The  $R^2$  values for all endogenous variables are presented in Table 6.

**Table 6.** Coefficients of determination ( $R^2$ ) for the endogenous constructs

Endogenous Construct	Planning	Innovation	Capabilities	Future-Proofing
$R^2$	0.134	0.153	0.157	0.411

Source: Generated from the survey data using SmartPLS 4. data using SmartPLS 4

In addition to evaluating the explanatory power of the structural model, effect sizes ( $f^2$ ) were examined to assess the relative contribution of each exogenous construct to the endogenous variables. As presented in Table 7, the results indicate varying magnitudes of effect across the structural relationships, reflecting differences in the strength of influence among the model paths.

**Table 7.** Effect size ( $f^2$ ) Values for the structural model relationships

Structural Path	$f^2$
Capabilities → Future-Proofing	0.312
Drivers → Planning	0.186
Planning → Capabilities	0.180
Planning → Innovation	0.155
Planning → Future-Proofing	0.080
Innovation → Future-Proofing	0.000

Note:Generated from the survey

## 6 Discussion

This discussion interprets the results of the structural model in light of the proposed theoretical framework and the literature on hospital infrastructure systems as complex socio-technical systems. Particular attention is given to the Iraqi institutional context, which is characterized by policy volatility and systemic uncertainty. The discussion examines how institutional drivers, planning practices, innovation, and design capabilities interact to shape future-proofing and mitigate functional and operational obsolescence.

### • Institutional Drivers and Planning Practices (H1):

The findings reveal a positive and statistically significant effect of institutional and contextual drivers on planning practices ( $\beta = 0.367, p < 0.001, f^2 = 0.186$ ), indicating a moderate explanatory effect. This result confirms that planning decisions in hospital projects are structurally shaped by regulatory, political, and economic frameworks. They do not operate within an isolated domain. In the Iraqi context, where policy instability and compressed timelines prevail, institutional conditions exert a measurable influence on planning logic. This supports the argument that long-term performance deficiencies often originate at the governance and planning levels rather than at the stage of detailed implementation stage.

### • Planning as a Systemic Mediator (H2 and H3)

Planning practices exert a statistically significant positive influence on innovation ( $\beta = 0.391, p < 0.001, f^2 = 0.155$ ) and on design capabilities ( $\beta = 0.396, p < 0.001, f^2 = 0.180$ ). The effect size is slightly stronger for design capabilities. This suggests that planning primarily functions as an implementation-enabling mechanism rather than merely stimulating conceptual innovation. These results position planning as the central mediating layer within

the system. Through planning, institutional pressures are translated into technological initiatives and executable system adaptability. In institutionally unstable environments, this mediating role becomes particularly critical.

- Innovation and Its Conditional Role (H4)

One of the most theoretically significant findings is the absence of a statistically significant direct effect of innovation on future-proofing ( $\beta = -0.017$ ,  $p < 0.850$ ,  $f^2 = 0.000$ ). The negligible effect size indicates that innovation alone does not meaningfully contribute to long-term adaptive capacity in this context. This finding challenges innovation-centric assumptions that frequently appear in hospital infrastructure systems discourse. It suggests that technological advancement, when embedded within rigid system and organizational frameworks, may increase systemic complexity without improving adaptability. In the Iraqi setting, technological initiatives are sometimes introduced under funding or political pressure without sufficient planning integration. Under such conditions, innovation may function as a contingent rather than an autonomous mechanism.

It is also important to clarify that the innovation construct in this study represents an aggregate latent dimension. It encompasses technological, process-oriented, and conceptual innovation initiatives within hospital projects. Rather than isolating each subtype, the model conceptualizes innovation as an integrated strategic posture that reflects the overall innovation orientation of the project environment. This aggregation supports theoretical parsimony and structural coherence. However, it may also conceal differentiated effects among specific forms of innovation. Accordingly, the absence of a direct effect should not be interpreted as evidence that all forms of innovation are ineffective. Instead, it indicates that innovation, when modeled as a composite construct, does not independently generate adaptive performance without planning integration and execution-oriented implementation capacity. Future research may therefore benefit from disaggregating innovation sub-dimensions to explore differentiated pathways within complex healthcare systems.

- Design Capabilities as the Core Driver (H6)

Design capabilities exhibit the strongest direct effect on future-proofing ( $\beta = 0.514$ ,  $p < 0.001$ ,  $f^2 = 0.312$ ), indicating a large effect size. This finding suggests that long-term adaptability in hospital infrastructure systems is more strongly associated with implementation-oriented capabilities such as flexibility, changeability, maintainability, and expansion capacity than with the other direct predictors in the model. Although planning practices also show a statistically significant direct effect on future-proofing, their contribution is comparatively smaller. This indicates that planning remains important, but its influence becomes more effective when it is translated into implementable capabilities that can be activated during operation.

The magnitude of the relationship between design capabilities and future-proofing supports the interpretation that sustained system performance depends not only on strategic planning or innovation intentions, but also on the extent to which adaptability is materially embedded in the system configuration and operational logic. In this sense, design capabilities function as a key implementation mechanism through which long-term performance requirements are realized in practice.

- Mediation Dynamics (H7)

Mediation analysis further confirms that design capabilities mediate the relationship between planning practices and future-proofing. Taken together, these findings suggest that planning does not operate as an isolated managerial layer, but becomes most effective when translated into implementable design capacity. This interpretation brings the relationships among planning, design capabilities, and future-proofing into a more integrated explanatory pathway, thereby reducing the need to treat them as fragmented interpretations across the discussion.

- System-Level Explanatory Power

The structural model explains 41.1% of the variance in future-proofing ( $R^2 = 0.411$ ), indicating moderate explanatory power within a highly complex socio-technical environment. For a context characterized by institutional instability and operational uncertainty, this level of explained variance suggests that the proposed configuration captures a substantial portion of the mechanisms driving hospital adaptability.

- Management and Policy Implications

From a management and policy perspective, the findings suggest that future-proofing in hospital infrastructure systems is influenced less by technological sophistication alone and more by the coherence of planning structures and the strength of design execution capacity. In institutionally volatile environments, governance alignment and lifecycle-oriented planning appear to play a more influential role than innovation intensity by itself. Accordingly, engineering management decisions related to resource allocation, governance coordination, and planning integration may substantially shape long-term system performance in hospital infrastructure systems.

- Systems Engineering Alignment

From a systems engineering perspective, the proposed structural model may be interpreted as a multi-level requirement translation framework. Institutional and contextual drivers can be viewed as the external requirement environment that shapes system constraints and performance expectations. Planning practices function as the mechanism through which high-level policy and regulatory conditions are translated into project-level priorities and strategic trade-offs related to cost, flexibility, and lifecycle performance.

Innovation operates at the subsystem level by introducing technological variation; however, its contribution appears to depend on its integration within a coherent planning logic. Design capabilities represent the implementation layer through which lifecycle trade-offs are materially embedded in the system by means of modularity, maintainability, and adaptability. Future-proofing, therefore, may be understood as a lifecycle performance outcome emerging from aligned requirement translation and execution capacity rather than from isolated technological inputs alone.

This interpretation places the model in closer dialogue with systems engineering principles, particularly lifecycle trade-off management and structured requirements flow-down.

- **Practical and Contextual Implications**

From an engineering management and governance perspective, these findings suggest that hospital future-proofing is better understood not as a purely technological or structural condition, but as a coordinated systems outcome shaped by planning integration, governance coherence, and design execution capacity. In practical terms, this points to the potential value of strengthening cross-functional planning committees, embedding lifecycle cost evaluation into feasibility stages, formalizing requirement translation between policy and implementation teams, and institutionalizing staged review gates to reduce fragmentation.

In institutionally unstable environments such as Iraq, policy volatility, funding uncertainty, and coordination discontinuities can shift project priorities toward immediate delivery rather than long-term adaptability. Under such conditions, contingency planning may need to extend beyond technical redundancy to include governance-level flexibility, phased procurement strategies, modular expansion allowances, and scalable service infrastructure. Collectively, these adjustments may help reorient project management practice from short-term delivery optimization toward uncertainty management and long-term system resilience.

## **7 Conclusions**

Based on the proposed conceptual framework and the quantitative analysis conducted using PLS-SEM, this study draws several conclusions regarding the nature of future-proofing in hospital infrastructure systems, conceptualized as a systemic outcome emerging from the interaction of institutional, planning, and implementation-related variables. This conclusion is structured to distinguish between the study's principal empirical findings, its theoretical contributions to engineering management and systems research, its practical implications for hospital infrastructure planning and governance, and its limitations and directions for future research.

### **7.1 Principal Empirical Findings**

The findings suggest that future-proofing in hospital infrastructure systems does not arise directly from innovation or advanced technological solutions alone, but rather from the interaction between institutional and contextual drivers, planning practices, and design capabilities. The results indicate that planning practices function as a central mechanism influencing whether innovative initiatives are translated into long-term operational value or remain isolated interventions with limited impact on functional and operational obsolescence. Quantitative analysis further shows that design capabilities represent the strongest direct predictor of future-proofing, whereas innovation does not exhibit a statistically significant direct effect on long-term system performance in hospital infrastructure systems. Taken together, these findings suggest that long-term adaptability is shaped by the combined influence of institutional conditions, planning coherence, and implementation-oriented design capacity rather than by innovation alone.

### **7.2 Theoretical Contributions**

This study contributes to infrastructure systems research and engineering management scholarship by framing future-proofing as an emergent system-level performance condition rather than a linear outcome of a single technological or organizational variable. The findings indicate that planning integration and design execution capacity can be interpreted as governance-related mechanisms shaping long-term adaptability under institutional uncertainty. In contrast to perspectives that associate future-proofing primarily with technological flexibility or digital innovation, the results suggest that adaptive performance is more strongly linked to a structured causal configuration in which planning coherence and execution-oriented design capabilities play influential roles. By proposing an integrated explanatory model that clarifies both direct and indirect relationships among institutional drivers, planning practices, innovation, and design capabilities, the study strengthens the interpretation of hospitals as complex socio-technical infrastructures shaped by managerial and governance constraints.

### **7.3 Practical Implications for Hospital Infrastructure Systems Practice**

The results highlight the need to move hospital infrastructure practice away from isolated formal or purely technological solutions toward a more capability-oriented and system-oriented approach. This implies that design decisions should be assessed according to their contribution to flexibility, changeability, maintainability, and the system's ability to absorb functional transformation without major operational disruption. The findings also emphasize the importance of treating planning as a continuous strategic process rather than a one-time preliminary phase.

Planning that incorporates a long-term time horizon, effective stakeholder interaction, and uncertainty considerations appears more likely to enable innovation to generate sustainable operational value rather than additional systemic complexity.

#### 7.4 Practical Implications for Hospital Infrastructure Planning and Governance

At the institutional level, the findings suggest that weak organizational stability and fragmented governance may indirectly accelerate pathways of obsolescence by weakening planning practices and constraining the development of design capabilities. Improving long-term system performance in hospital infrastructure systems therefore appears to require institutional adjustments that support proactive planning, encourage a lifecycle perspective, and enable implementation teams to make flexible decisions beyond short-term compliance-oriented logic. For hospital governance, this implies strengthening planning continuity, reducing fragmentation in decision-making, and aligning regulatory and managerial processes with long-term adaptability objectives. Although the study is grounded in the Iraqi context, the identified mechanisms may also be relevant to other settings characterized by institutional fragility, rapid transformation, or post-reconstruction pressure.

#### 7.5 Limitations and Future Research

Despite its contributions, this study has several limitations. It is based primarily on the perspectives of professionals involved in hospital infrastructure planning and implementation, without direct integration of operational performance data or post-occupancy indicators. In addition, the proposed model was tested within a specific institutional context, which requires caution in extending the findings across all healthcare systems. These limitations open several directions for future research, including the incorporation of longitudinal operational data, comparative analysis across different institutional environments, and further investigation of advanced digital design tools within more mature planning frameworks. The model may also be extended by incorporating additional dimensions such as digital governance and institutional learning in healthcare systems.

#### 7.6 Recommendations

Based on the empirical findings of the validated structural model and the quantitative analysis conducted using PLS-SEM, this study proposes a set of applied and institutional recommendations aimed at enhancing future-proofing in hospital infrastructure systems, particularly in complex and institutionally unstable contexts. These recommendations should be understood as evidence-informed implications derived from the model rather than as universally prescriptive measures.

##### 7.6.1 Planning and implementation

- **Shifting from Solution-Oriented Design to Capability-Oriented Design:** Hospital infrastructure system practices should move beyond an exclusive focus on isolated formal or technological innovations toward a more capability-oriented design approach. This involves evaluating design decisions in terms of their contribution to long-term flexibility, adaptability, maintainability, and functional transition capacity, rather than prioritizing short-term compliance or aesthetic considerations alone. Such an approach may help align design outcomes with the operational realities and evolving demands of healthcare facilities over their lifecycle.

- **Integrating Future-Proofing Requirements into Early Planning Stages:** The findings of this study suggest that planning practices represent a key leverage point for enhancing future-proofing in hospital infrastructure systems. Accordingly, requirements related to long-term adaptability and change accommodation should be incorporated explicitly into early design briefs, system configuration strategies, and infrastructure planning frameworks, rather than being treated as secondary considerations introduced after design completion.

- **Strengthening Planning as a Continuous Strategic Process:** Planning should be understood not as a finite preliminary phase, but as a continuous strategic process extending across design, implementation, and operation. Such an approach may enable hospitals to respond more proactively to uncertainty and future change, thereby supporting stronger alignment between planning intentions and long-term operational performance.

##### 7.6.2 Institutional and governance

- **Enhancing Institutional Stability and Planning Continuity:** The findings suggest that institutional instability may indirectly accelerate pathways of functional and operational obsolescence by weakening planning practices and constraining the development of design capabilities. Accordingly, the study recommends governance arrangements that support planning continuity across successive political and funding cycles, so that long-term planning objectives are less vulnerable to short-term institutional fluctuation.

- **Adopting Lifecycle-Oriented Decision-Making Frameworks:** Regulatory systems and approval mechanisms should move beyond narrowly short-term cost- and compliance-driven logics toward more lifecycle-oriented evaluation frameworks. Such frameworks should explicitly consider adaptability, operational disruption, and long-term

value creation in healthcare infrastructure systems, thereby aligning institutional decision-making more closely with future-proofing objectives.

• **Empowering Implementation Teams to Make Adaptive Decisions:** The study also recommends granting architects, planners, and implementation teams greater latitude to support adaptive decision-making across different project phases. Overly rigid regulatory standards may need to be reconsidered where they constrain flexibility, as such constraints can reduce the capacity of hospital infrastructure systems to respond to future functional, technological, and organizational change.

#### 7.6.3 Innovation strategy

• **Repositioning Innovation as an Enabling Rather Than a Leading Variable:** In light of the absence of a statistically significant direct effect of innovation on future-proofing, innovation strategies may be more appropriately understood as conditional enabling mechanisms rather than primary drivers. The findings suggest that innovation is more likely to generate tangible value when it is aligned with robust planning practices and well-developed design capabilities, rather than being pursued as an isolated objective.

• **Aligning Technological Innovation with System and Organizational Readiness:** The introduction of digital or technological solutions should be accompanied by adequate spatial, organizational, and operational readiness, including maintenance and facility management capacity, to support them over the long term. Such alignment may reduce the risk of innovation becoming an additional source of system complexity rather than a contributor to adaptive performance.

#### 7.6.4 Future research

• **Integrating Post-Occupancy and Operational Performance Data:** Future research may benefit from integrating professional perception data with longitudinal post-occupancy and operational performance data, thereby strengthening the interpretation of future-proofing mechanisms in hospital infrastructure systems.

• **Conducting Comparative Studies Across Institutional Contexts:** Comparative studies across diverse governance, regulatory, and reconstruction contexts may help assess the broader applicability of the proposed model and strengthen its explanatory relevance beyond a single institutional setting.

### Author Contributions

Conceptualization, M.J.K.; methodology, M.J.K.; software, A.Z.K.A.; validation, E.S.A.; formal analysis, M.J.K.; investigation, M.J.K.; resources, M.J.K.; data curation, A.Z.K.A.; writing—original draft preparation, M.J.K.; writing—review and editing, E.S.A. and A.Z.K.A.; visualization, M.J.K.; supervision, E.S.A.; project administration, M.J.K. All authors have read and agreed to the published version of the manuscript.

### Data Availability

The data used to support the research findings are available from the corresponding author upon request.

### Conflicts of Interest

The authors declare no conflicts of interest.

### References

- [1] W. J. Glover, N. Nissinboim, and E. Naveh, “Examining innovation in hospital units: A complex adaptive systems approach,” *BMC Health Serv. Res.*, vol. 20, no. 1, pp. 554–554, 2020. <https://doi.org/10.1186/s12913-020-05403-2>
- [2] M. Jaušovec and B. Gabrovec, “Architectural evaluation of healthcare facilities: A comprehensive review and implications for building design,” *Buildings*, vol. 13, no. 12, pp. 2926–2926, 2023. <https://doi.org/10.3390/buildings13122926>
- [3] S. Ibrahim, S. Al-Dahir, T. Al Mulla, F. Lami, S. M. M. Hossain, A. Baqui, and G. Burnham, “Resilience of health systems in conflict affected governorates of Iraq, 2014–2018,” *Confl. Health*, vol. 15, no. 76, 2021. <https://doi.org/10.1186/s13031-2021-00412-2>
- [4] C. Truppa, S. Yaacoub, M. Valente, G. Celentano, L. Ragazzoni, and D. Saulnier, “Health systems resilience in fragile and conflict-affected settings: A systematic scoping review,” *Confl. Health*, vol. 18, no. 2, 2024. <https://doi.org/10.1186/s13031-2023-00560-7>
- [5] N. J. Sebire, A. Adams, L. Arpiainen, L. Celi, A. Charlesworth, M. Gorgens, F. Magrabi, Y. Nagasawa, C. Onoka, and M. McKee, “The future hospital in global health systems: The future hospital as an entity,” *Int. J. Health Plann. Manag.*, vol. 40, no. 3, pp. 730–740, 2025. <https://doi.org/10.1002/hpm.3893>
- [6] S. Memari, T. Kocaturk, M. Lozanovska, F. Andrews, and R. Tucker, “Future proofing for hospital building design: From research to practice,” *Archit. Eng. Des. Manag.*, vol. 19, no. 6, pp. 681–700, 2023. <https://doi.org/10.1080/17452007.2022.2162842>

- [7] G. Scialpi and J. Declercq, "Adaptability in healthcare buildings: A perspective through Joseph Bracops hospital," *Front. Med. Technol.*, vol. 5, no. 1199581, 2023. <https://doi.org/10.3389/fmedt.2023.1199581>
- [8] L. M. Pereira and S. W. Ornstein, "A systematic literature review on healthcare facility evaluation methods," *HERD Health Environ. Res. Des. J.*, vol. 16, no. 3, pp. 338–361, 2023. <https://doi.org/10.1177/19375867231166094>
- [9] E. Martens, H. U. Haase, G. Mastella, A. Henkel, C. Spinner, F. Hahn, C. Zou, A. F. Sanches, J. Allescher, and D. Heid, "Smart hospital: Achieving interoperability and raw data collection from medical devices in clinical routine," *Front. Digit. Health*, vol. 6, no. 1341475, 2024. <https://doi.org/10.3389/fdgth.2024.1341475>
- [10] N. J. Sebire, A. Adams, L. Celi, A. Charlesworth, M. Gorgens, M. Gorsky, O. Landeg, Y. Nagasawa, K. T. Nimako, and C. Onoka, "The future hospital in global health systems: The future hospital within the healthcare system," *Int. J. Health Plann. Manag.*, vol. 40, no. 3, pp. 741–751, 2025. <https://doi.org/10.1002/hpm.3891>
- [11] E. Mori, F. Cantoni, P. G. Bisogni, and E. Zuffada, "Hospitals' resilience: An evidence-based framework for sustaining the 'coping' phase in non-linear and continuous crises," *J. Public Aff.*, vol. 25, no. 4, pp. e70 085–e70 085, 2025. <https://doi.org/10.1002/pa.70085>
- [12] A. Kumar, S. S. W. Lam, S. L. Chan, Y. Xu, Y. Ge, G. K. T. Gui, and H. K. Tan, "Strategizing towards the future hospital: A systems thinking approach," *Health Res. Policy Syst.*, vol. 23, no. 71, 2025. <https://doi.org/10.1186/s12961-025-01333-9>
- [13] Y. Li, P. Liao, Y. Song, and H. Chi, "A systematic decision-support approach for healthcare facility layout design integrating resource flow and space adjacency optimization with simulation-based performance evaluation," *J. Build. Eng.*, vol. 77, no. 107465, 2023. <https://doi.org/10.1016/j.jobe.2023.107465>
- [14] A. S. Alabi, O. A. Alabi, T. E. Adebakin, and B. T. Alayande, "Revisiting literature on building quality of healthcare facilities between developed and developing countries: Scoping review," *Int. J. Build. Pathol. Adapt.*, vol. 44, no. 3, pp. 809–832, 2025. <https://doi.org/10.1108/IJBPA-11-2024-0241>
- [15] E. Alsaedi and M. Altaie, "Factors affecting maintenance practises in Iraq's hospital buildings," *Jordan J. Civ. Eng.*, vol. 17, no. 3, pp. 408–418, 2023. <https://doi.org/10.14525/JJCE.v17i3.04>
- [16] S. Chansanguan, N. Rittippant, Y. Ueki, and C. Jeenanunta, "Sustainable digital transformation in public hospitals: Strategic enablers for smart healthcare systems," *Sustainability*, vol. 17, no. 19, pp. 8614–8614, 2025. <https://doi.org/10.3390/su17198614>
- [17] E. W. Barasa, S. Molyneux, M. English, and S. Cleary, "Hospitals as complex adaptive systems: A case study of factors influencing priority setting practices at the hospital level in Kenya," *Soc. Sci. Med.*, vol. 174, pp. 104–112, 2017. <https://doi.org/10.1016/j.socscimed.2016.12.026>
- [18] S. Grimaz, E. Ruzzene, and F. Zorzini, "Situational assessment of hospital facilities for modernization purposes and resilience improvement," *Int. J. Disaster Risk Reduct.*, vol. 66, no. 102594, 2021. <https://doi.org/10.1016/j.ijdrr.2021.102594>
- [19] B. Askar, L. Bragança, and H. Gorgolewski, "Adaptability of buildings: A critical review on the concept evolution," *Appl. Sci.*, vol. 11, no. 10, pp. 4483–4483, 2021. <https://doi.org/10.3390/app11104483>
- [20] D. Al Asfoor, C. Tabche, M. Al-Zadjali, A. Mataria, S. Sheikh, and S. Rawaf, "Concept analysis of health system resilience," *Health Res. Policy Syst.*, vol. 22, no. 1, p. 43, 2024. <https://doi.org/10.1186/s12961-024-01114-w>
- [21] S. Memari, T. Kocaturk, M. Lozanovska, F. Andrews, and R. Tucker, "The interdisciplinary conceptualization of future proofing in the context of hospital buildings," *Build. Res. Inf.*, vol. 50, no. 7, pp. 810–826, 2022. <https://doi.org/10.1080/09613218.2021.2011704>
- [22] O. Golburean, E. S. Nordheim, A. Faxvaag, R. Pedersen, O. Lintvedt, and L. Marco-Ruiz, "A systematic review and proposed framework for sustainable learning healthcare systems," *Int. J. Med. Inform.*, vol. 192, no. 105652, 2024. <https://doi.org/10.1016/j.ijmedinf.2024.105652>
- [23] K. M. Thu, S. Bernays, and S. Abimbola, "A literature review exploring how health systems respond to acute shocks in fragile and conflict-affected countries," *Conflict Health*, vol. 16, no. 1, p. 60, 2022. <https://doi.org/10.1186/s13031-022-00484-8>
- [24] F. Pascale and N. Achour, "Envisioning the sustainable and climate resilient hospital of the future," *Public Health*, vol. 237, pp. 435–442, 2024. <https://doi.org/10.1016/j.puhe.2024.10.028>
- [25] L. Elstow, F. R. Parra, and K. MacAskill, "Tracking climate adaptation in hospitals: An inventory of structural measures," *Clim. Risk Manag.*, vol. 46, p. 100657, 2024. <https://doi.org/10.1016/j.crm.2024.100657>
- [26] S. Rajagopal, V. Balakrishnan, and Y. K. Chiam, "The direct effect of institutional factors on healthcare information systems (HIS) organisational interoperability in Malaysian public hospitals," *Health Inform. J.*, vol. 30, no. 4, pp. 1–19, 2024. <https://doi.org/10.1177/14604582241294218>
- [27] T. Yang, M. White, R. Lipson-Smith, M. M. Shannon, and M. Latifi, "Design decision support for healthcare architecture: A VR-integrated approach for measuring user perception," *Buildings*, vol. 14, no. 3, p. 797, 2024. <https://doi.org/10.3390/buildings14030797>

- [28] G. Kucan, T. Tan, D. Grossmann, K. Graser, and D. M. Hall, "Sustainable future-proofing healthcare facilities: A modular and adaptable design approach," *J. Manag. Eng.*, vol. 40, no. 6, pp. 04 024 053–04 024 053, 2024. <https://doi.org/10.1061/JMENEA.MEENG-5942>
- [29] S. Memari, T. Kocaturk, M. Lozanovska, F. Andrews, and R. Tucker, "Architect insights: Implications and barriers of future-proofing hospitals," *Health Environ. Res. Des. J.*, vol. 19, no. 1, pp. 109–126, 2025. <https://doi.org/10.1177/19375867251374676>
- [30] J. F. Hair and A. Alamer, "Partial least squares structural equation modeling (PLS-SEM) in second language and education research: Guidelines using an applied example," *Res. Methods Appl. Linguist.*, vol. 1, no. 3, p. 100027, 2022. <https://doi.org/10.1016/j.rmal.2022.100027>
- [31] J. F. Hair, M. Sarstedt, C. M. Ringle, and S. P. Gudergan, *Advanced Issues in Partial Least Squares Structural Equation Modeling*. Sage, 2018.
- [32] J. Henseler, C. M. Ringle, and M. Sarstedt, "A new criterion for assessing discriminant validity in variance-based structural equation modeling," *J. Acad. Mark. Sci.*, vol. 43, no. 1, pp. 115–135, 2015. <https://doi.org/10.1007/s11747-014-0403-8>
- [33] C. M. Ringle, M. Sarstedt, R. Mitchell, and S. P. Gudergan, "Partial least squares structural equation modeling in HRM research," *Int. J. Hum. Resour. Manag.*, vol. 31, no. 12, pp. 1617–1643, 2020. <https://doi.org/10.1080/09585192.2017.1416655>
- [34] D. L. Bandalos, *Measurement Theory and Applications for the Social Sciences*. New York, NY: Guilford Press, 2018.
- [35] C. Fornell and D. F. Larcker, "Evaluating structural equation models with unobservable variables and measurement error," *J. Mark. Res.*, vol. 18, no. 1, pp. 39–50, 1981. <https://doi.org/10.2307/3151312>
- [36] P. M. Podsakoff, S. B. MacKenzie, and N. P. Podsakoff, "Sources of method bias in social science research and recommendations on how to control it," *Annu. Rev. Psychol.*, vol. 63, pp. 539–569, 2012. <https://doi.org/10.1146/annurev-psych-120710-100452>
- [37] S. P. Gudergan, O. I. Moisescu, L. Radomir, C. M. Ringle, and M. Sarstedt, "Special issue editorial: Advanced partial least squares structural equation modeling (PLS-SEM) applications in business research," *J. Bus. Res.*, vol. 188, p. 115087, 2025. <https://doi.org/10.1016/j.jbusres.2024.115087>