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Building Adaptations and Laboratory Safety Concerns: A Case Study of High-Rise Academic Laboratories in a Thai University

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ABSTRACT

Academic laboratory buildings face unique challenges due to the dynamic nature of laboratory tasks, technological advancements, and the utmost importance of maintaining safety. While flexible design strategies are recommended for laboratory facilities, there is a need to explore the empirical evidence of building adaptations and their impact on safety in real-world cases. This study employs a case study approach to investigate how academic laboratory buildings have been adapted to changing requirements and the resulting implications for laboratory safety. Four high-rise academic laboratories on a university campus were selected as case studies, and data were collected through as-built and updated architectural drawings, on-site walk-through surveys, and laboratory safety inspection reports. The findings reveal that adaptable design strategies, specifically those related to "long life" and "loose fit," have been implemented and are commonly used. However, building adaptations often occur independently, and without a proper understanding of the original design strategies, leading to laboratory safety problems caused by inappropriate adaptations. The proposed conceptual model aims to elaborate on the relationship between building adaptations and laboratory safety concerns. Further research should focus on investigating the patterns of adaptations of building layers using a time-series approach, and developing facility management strategies to effectively address dynamic safety conditions.

Keywords: adaptability, building adaptation, laboratory safety, design strategy, high-rise buildings

INTRODUCTION

Academic laboratories are critically important in advancing scientific research as they provide essential spaces for conducting experimental work and facilitate practical learning experiences for students (Abbas et al., 2016; Bai et al., 2022). Therefore, ensuring the safety of laboratory personnel and maintaining a safe environment is of utmost importance (Ménard & Trant, 2020).

The design of laboratory facilities and building systems is a key factor in maintaining laboratory safety, and good design requires the coordination of various design strategies and engineering controls in accordance with laboratory safety regulations (DiBerardinis, 2016; DiBerardinis et al., 2013; Ruys, 1990; Watch, 2002; Watch & Tolat, 2017). However, the dynamic nature of laboratory tasks and the involvement of hazardous substances pose challenges with respect to safety regulations and design guidelines, and persistently lead to laboratory safety problems (Ezenwa et al., 2022; National Research Council [NRC], 2011; The National Institute for Occupational Safety and Health [NIOSH], 2023; Yunfei, 2022).

Furthermore, the natural progression of the building life cycle assumes the deterioration of building elements and utilities over time, necessitating maintenance, refurbishment, and building adaptations (Douglas, 2006). The continuous changes in building conditions, occupancy, and laboratory safety regulations further exacerbate issues related to outdated facilities or inadequate building engineering systems, underscoring the importance of flexibility and adaptability in laboratory facilities (Kamara et al., 2020; Palluzi, 2021; Wiriyakraikul et al., 2022a; 2022b). While research on building adaptations has been extensively conducted for various building types, further investigation is required, specifically in the context of academic laboratory facilities.

This paper examines the relationship between adaptability and safety concerns in complex and high-risk structures, specifically focusing on high-rise academic laboratory buildings. The conceptual model is developed through a literature review and insights from studying four case studies of high-rise academic laboratory buildings in Thailand. The primary objective of this paper is to investigate adaptable design strategies implemented in the design of these laboratory buildings, the adaptations of physical elements, and their impact, particularly in relation to safety concerns.

LITERATURE REVIEW

This section draws upon two key concepts for the development of the framework: (1) The concept of laboratory safety, and (2) the concept of flexibility and adaptability.

Laboratory Safety

The concept of laboratory safety

Safety is 'the condition of being protected from or unlikely to cause danger, risk, or injury' (Oxford English Dictionary, n.d.). The concept of safety and accident prevention is derived from epidemiology, in which the cause of an injury is described as an interaction of several factors. The amount of energy necessary to cause injury varies with the damage threshold of the susceptible host (Fuscaldo, 2012). Therefore, laboratory safety can be achieved by controlling the relationship between hazard exposure and control measures.

"The Hierarchy of Controls" is a standard model for determining actions to maintain safety by removing, reducing, or controlling hazards. There are five levels in order of action based on general effectiveness, including (1) elimination, (2) substitution, (3) engineering controls, (4) administrative controls, and (5) personal protective equipment (PPE) (NIOSH, 2023). Laboratory risks are also mitigated by ensuring the safe handling and management of laboratory hazards according to prudent practices (Kuzmina et al., 2022; NRC, 2011; Walters et al., 2017). Local safety management guidelines and routine academic laboratory inspections also play essential roles (Wyllie et al., 2016).

In Thailand, the Enhancement of Safety Practice in Research Laboratory (ESPReL) inspection checklist has been established and enforced as the National Standard (Thai Industrial Standard Institute TIS 2677) for laboratory safety inspection since 2015 (Phanngam & Panyakapo, 2021; Wiriyakraikul, 2015; Wiriyakraikul et al., 2022a). The ESPReL inspection serves as a comprehensive tool to assess laboratory safety conditions and enhance awareness regarding general laboratory safety practices. Due to its proven effectiveness, Thai universities now mandate that annual safety inspections be conducted using the ESPReL checklist for their laboratories.

This ESPReL checklist includes a total of 162 items from seven main interrelated safety components, as illustrated in Figure 1. Within the aspect of physical characteristics of the laboratory, there are 48 items divided into seven subcategories: (1) architecture, (2) interior design: furniture, tools, and equipment, (3) structural engineering, (4) electrical and lighting engineering, (5) sanitary and environmental engineering, (6) ventilation and air-conditioning system, and (7) emergency and communication system.

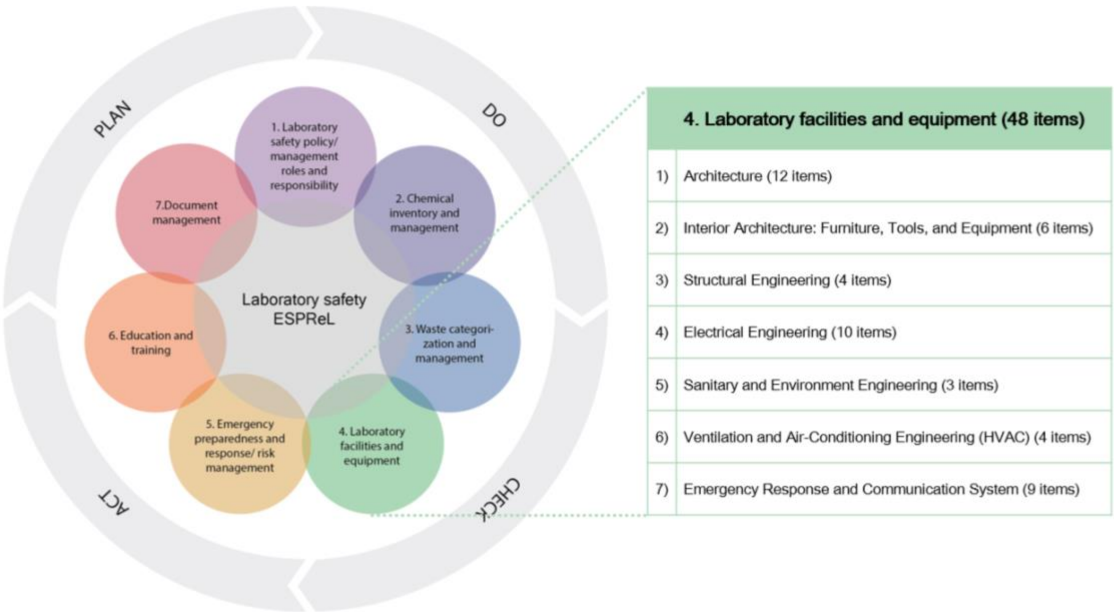
A review of academic laboratory safety research suggests that further studies be undertaken on academic lab safety, including the occurrence of lab accidents, factors contributing to lab accidents, safety training, and cultural barriers to implementing safer lab practices (Ménard & Trant, 2020; Yang et al., 2019). In particular, there is a need for further investigation into safety issues related to the physical features of laboratory facilities (Kim et al., 2005; Wiriyakraikul et al., 2022a), highlighting the significance of adequate design and maintenance (Abbas et al., 2016; Lavy, 2008) to ensure a safe working environment.

Laboratory design guidelines

The design considerations for laboratories vary depending on the hazardous substances involved and levels of associated risks (Furr, 2000; Occupational Safety and Health Administration [OSHA], 2011; Rayburn, 1990). In addition, designing and constructing a safe laboratory building requires the collaboration of multidisciplinary professionals and the integration of every stakeholder's needs (Goode & Tucker, 2020). Therefore, incorporating the design for laboratory safety in the early design stage, and providing guidance on methods for dealing with a variety of hazards, should help the team members to create safe built environments and implement safe practices during the design,

Figure 1

The Enhancement of Safety Practice of Research Laboratory (ESPReL) Framework



Note. Adapted from *ESPReL Knowledge Platform*, by National Research Council of Thailand, 2023 (https://labsafety.nrct.go.th/). Copyright 2023 by National Research Council of Thailand.

construction, and post-occupancy phases (Mourya et al., 2014; Rasool et al., 2016; Turkoglu, 2012; Weaver, 2010; Whitney, 2016).

Laboratory design guidelines are continuously developed, and they incorporate important design considerations that focus primarily on safety and efficiency (DiBerardinis et al., 2013; Furr, 2000; Hassanain et al., 2020; Ruys, 1990; Watch, 2002). In addition, adequate design of a facility can also lead to enhanced productivity and comfort (Hassanain et al., 2019; Sanni-Anibire et al., 2018), energy efficiency (Mills & Sartor, 2005; Musau & Steemers, 2007; Woolliams et al., 2005), and sustainability (Dittrich, 2015).

Recent studies have focused on developing design guidelines for functional efficiency (Hassanain et al., 2020b). These efforts involve identifying Key Performance Indicators (KPIs) to assess the performance of academic and research laboratory facilities (Mahmoud et al., 2019) and conducting Post-Occupancy Evaluation (POE) (Hassanain et al., 2020a). The findings emphasise that the development of KPIs should be tailored to the specific context of each laboratory, and should consider the diverse nature of laboratories in general, and the concerns of the stakeholders involved.

However, despite the continuous development of laboratory design guidelines and the current trend of increased building density in the urban context, the adaptability and safety concerns of laboratory buildings in the context of high-rise building typology have rarely been discussed. Further research on this building typology is crucial due to the highly complex elements and existing design challenges, particularly in terms of structural and fire safety (Ma & Guo, 2012; Song et al., 2022).

Flexibility and Adaptability

The concept of flexibility and adaptability

Buildings both deteriorate and become obsolete as they age, and, thus, require adaptation. A building's physical life, which may be interpreted in the context of its structural adequacy or safety, is effectively reduced by obsolescence, resulting in its useful life being somewhat less than its expected physical life (Langston, 2011). Deterioration is inevitable as an ageing process, but can be controlled to a certain degree by selecting appropriate materials at the design stage, adopting adequate construction practices, and carrying out regular maintenance and adaptation (Douglas, 2006; Silva et al., 2021). On the other hand, obsolescence does not equate to defective performance (Langston, 2011). Instead, it refers to the gradual process of a building becoming increasingly unable to meet contemporary standards regarding functionality, regulatory statutes, physical structure, and economics within a particular place or time, causing the building to become obsolete (Butt et al., 2015). In addition, obsolescence is not easily predictable, and is affected by economic, functional, technological, social, legal, and even political factors (e.g., Douglas, 2006; Mansfield, 2000; Seeley, 1983). Therefore, building deterioration and obsolescence are directly involved with the need for building adaptations (Douglas, 2006; Wilkinson, 2012).

Adaptation includes any work to a building that can be considered ‘over and above’ standard maintenance; such work is undertaken to change the building’s capacity, function, or performance (Douglas, 2006). Even though no definition of the term has been universally agreed upon (Pinder et al., 2017; Schmidt III et al., 2010), "adaptability" can be defined as "the capacity of a building to accommodate effectively the evolving demands of its context, thus maximising value through its life" (Schmidt III et al., 2010, p. 235). The definition highlights four key characteristics involved, namely, the capacity for change, the ability of the building to remain fit for purpose, value, and the speed of change (Kamara et al., 2020; Schmidt III et al., 2010). Schmidt III et al. (2010) built upon earlier definitions by defining six types of adaptabilities related to the type and frequency of changes: adjustable, versatile (flexible), refitable, convertible, scalable, and movable.

The essential theoretical background for adaptable buildings stems from the concept of building layers (Schmidt III & Austin, 2016). Duffy (1990) classified a building’s physical and temporal layers into four layers: Shell, Service, Scenery, and Set. The concept acknowledges that building elements have different lifespans, and that they should be constructed distinctly.

Brand (1995) expanded Duffy's concept by seeing its components as a set of "shearing layers" that change at different rates. The layers comprise "site," "structure," "skin," "services," "space plan," and "stuff." The more these layers are connected, the greater difficulty and cost of adaptation, suggesting that the design will be governed by slow-changing components. The main advantage of this approach is the addition of time (longevity) to the building layers, opening new perspectives on design, maintenance, and building restoration (Estaji, 2017).

The conceptual model of building adaptability includes both modifications made by building users and changes made to the physical structure of the building. These elements are summarised in Figure 2. The term "building systems" encompasses the building's physical structure, its users, and other stakeholders who have a direct impact on its use and operations. The triggers for change refer to various events or actors, which can be internal or external to the building (Kamara et al., 2020).

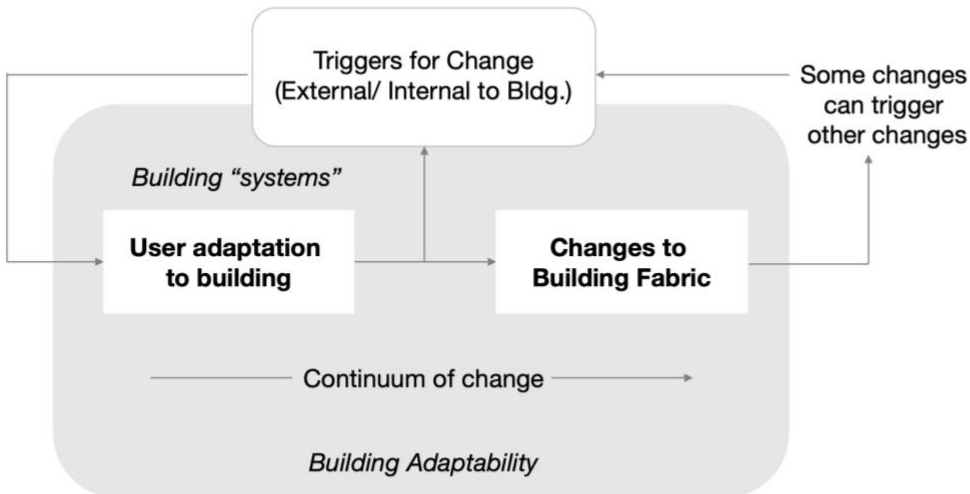
Adaptable design strategies

Adaptability has been investigated and promoted as a design strategy in various building types, including offices, commercial buildings, housing, and healthcare facilities (Schmidt III & Austin, 2016). For example, Arge (2005) identified adaptable design strategies in office buildings, including generality, flexibility, and elasticity, and highlighted how different design approaches taken by owner-occupiers and developers affected adaptability. Key design considerations for adaptable buildings include location and orientation of the original building, space around the building, selection and availability of materials and products, foundation and basement design, distribution, capacity of services, means of access and egress, size and layout of the structural grid, and legal restraints (Douglas, 2006).

Most key design factors affecting the building's adaptability were explored through literature review. Gosling et al. (2013) identified two key enablers: (1) design enablers for flexibility (including interchangeable components, level of indeterminacy, layering of building elements. and strategies for deconstruction), and (2) process flexibility (including flexibility in the planning/

Figure 2

Conceptual Model of Change and Building Adaptability



Note. Adapted from "Change Factors and the Adaptability of Buildings," by J.M. Kamara, O. Heidrich, V.E. Tafaro, S. Maltese, M.C. Dejaco, and F.Re Cecconi, 2020, *Sustainability, 12*(16), p. 5 (https://dx.doi.org/10.3390/su12166585). Copyright 2020 by John.M. Kamara, Oliver Heidrich, Vincenza E. Tafaro, Sebastiano Maltese, Mario C. Dejaco, and Fulvio Re Cecconi.

project process, supply chain integration, and supply chain flexibility).

Another study by Ross et al. (2016) incorporated a literature review to identify eleven "design-based enablers," and surveyed design professionals to rate their effectiveness. The findings show that the most effective design-based enablers comprise accurate information about the building (Plans), the reserve capacity in building systems (Reserve), the separation of building systems according to their rate of replacement (Layer), and interior spaces that are free of structural and other elements that cannot be easily removed (Open).

Another study by Black et al. (2019) categorised Ross et al. (2016) design-based enablers into four groups, namely, "long life," "loose fit," "layer separation," and "reduce uncertainty," for investigating physical features that facilitate or impede building adaptations (Table 1). The findings revealed a wide range of physical factors associated with the adaptability of buildings. Nevertheless, most studies indicate the lack of empirical evidence related to implementing these design enablers and suggest further studies investigating the effectiveness of adaptable design strategies in real-world cases (Black et al., 2019; Ross et al., 2016).

Flexibility and adaptability of laboratory facilities

In the context of laboratory facilities, studies are still needed that relate to building adaptations and design strategies. Most design guidelines suggest design strategies for flexibility that include such concepts as implementing a modular design approach, open-plan laboratory layout, mobile casework and movable laboratory furniture, modular distribution of building utilities with flexible connections of engineering services, provision of interstitial floors/spaces, etc. (Baum & Diberardinis, 2006; Braun, 2005; DiBerardinis et al., 2013; Watch, 2002; Watch & Tolat, 2017). The most comprehensive conceptual framework relating to the flexibility and adaptability of laboratory facilities dates back to the 1990s.

Table 1

Adaptable Design-Based Enablers From Previous Studies

Long life	Loose fit	Layer separation	Reduce uncertainty
• Reserve strength	• Open floor • Appropriate structural span/building section (floor-to-floor height)	• Building systems built as layers	• Availability of accurate plans
• Quality and durable materials	• Simple design	• Access to building systems	• Common building components
		• Modular components	• Simple design
		• Simplicity of connections	• Quality materials
		• Design for deconstruction (DfD)	• Access to building systems

Note. Adapted from "Identifying Physical Features that Facilitate and Impede Building Adaptation," by A. K. Black, B.E. Ross, and Z. Rockow, 2019, *Sustainability in Energy and Buildings 2018: Proceedings of the 10th International Conference in Sustainability on Energy and Buildings (SEB'18) 10*, p.54 (https://doi.org/10.1007/978-3-030-04293-6_6). Copyright 2019 by Springer Nature Switzerland AG.

Figure 3

Flexibility Concept for Laboratory Buildings

	Flexibility Type	Rate of Change	Speed of Change	Construction Approach
Structures	Versatile	Hardly ever	Slow	Built-in place
Utilities				
	Convertible	Sometimes	Medium	Modular parts Portable components
Space Delineation				
	Rearrangable	Often	Fast	Mobile components
Furnishings				

Note. Adapted from *Handbook of Facilities Planning: Laboratory Facilities (Vol.1)* (p.178), by T. Ruys, 1990, Van Nostrand Reinhold Company. Copyright 1990 by Theodorus Ruys.

A study by Ruys (1990) separated the physical elements of laboratory facilities into four layers, namely, structures, utilities, space delineation, and furnishings. This set of guidelines indicates that appropriate design of building elements and the right construction approach can facilitate flexibility, including "versatility," "rearrange-ability," and "convertibility" (Figure 3). In addition, Ruys (1990) identified possible conflicts between adaptability and safety. As the ability to physically alter parts of the environment increases, the opportunity to create safety problems runs parallel to or even ahead of that ability.

Nevertheless, the empirical evidence is still lacking regarding the effectiveness of these strategies, the adaptability of building elements of existing laboratory facilities, and the relationship between adaptability and safety of laboratory facilities. Making strides in this area of research should contribute to the enhancement of facility safety through appropriate adaptations of existing facilities and mitigation of building obsolescence. Moreover, it could feed forward into adjustments to adaptable design strategies for newly built facilities.

RESEARCH METHODOLOGY

Development of the Conceptual Framework

The literature review in the previous section led to the development of a conceptual framework for investigating the relationship between adaptability and safety in laboratory buildings. The hypothesis is that adaptability of the building, either involving users' adaptations or changes to the physical elements of the building, could impact the safety conditions of the laboratory. Given that safety is of paramount concern in this building typology, the framework emphasises the importance of integrating safety considerations throughout the process of building adaptations.

Methodology

The development of the conceptual model is guided by four main research questions in this paper:

1) What are the characteristics of the building elements, and which adaptable design strategies are implemented?

2) How have the building elements changed over time?

3) How do building adaptations affect laboratory safety?

4) What is the conceptual framework for enabling an "adaptable" and "safe" academic laboratory?

This research employs a case study approach to exploring the relationship between building adaptations and laboratory safety in university laboratories. Given that various internal and external factors influence these variables, an inductive approach is employed to comprehensively understand the phenomena from multiple perspectives. Qualitative data is gathered from multiple cases, allowing for a thorough examination of the research problem within its real-life context (Groat & Wang, 2013).

The methodological flow (Figure 4) encompassed two key processes: (1) data collection and (2) analysis.

1. The data collection process consisted of two main parts: (1) gathering secondary sourced data, including as-built drawings and laboratory safety inspection reports of the case studies, and (2) conducting on-site investigation and documentation. The on-site investigation involved a thorough walk-through of each building, and taking of detailed notes, photographs, and video recordings. The collected information was utilised to update the current drawings, and to report on the current usage and building conditions.

2. The data analysis process primarily involved examining the original as-built drawings, supported by the literature review, to identify adaptable design strategies integrated into the buildings. The analysis of building adaptations was achieved by comparing the as-built drawings with the data gathered from on-site investigation. The final part focused on analysing safety concerns obtained from safety inspection reports and investigating their relationships to the design and adaptations of the building elements.

Case studies

The selection of case studies for this research prioritised high-rise academic laboratory buildings due to their complex building elements and design challenges (Shakir et al., 2021), particularly in terms of fire safety (Ma & Guo, 2012; Song et al., 2022) and adaptability (Arge, 2005; Von Borstel & Sigrist, 2010; Weener, 2021). High-rise buildings have been a significant focus of research in these areas for the past decade. Additionally, their increasing popularity in urban contexts, along with their lower likelihood of demolition compared to smaller buildings, makes this study more impactful for practical implementation now and in years to come.

The main criteria for selecting case studies were as follows:

- The selected buildings must all be located on the same university campus, and each must contain academic/research laboratory space.
- The selected buildings must have a laboratory safety inspection report (ESPReL checklist) completed and certified by a specialist committee.
- The building height must exceed seven storeys or 23 meters above ground level, as defined by building regulations in Thailand, categorising them as "high-rise buildings."
- The building must have a complete set of as-built drawings of architectural and related engineering systems.
- The selected buildings must be comparable in terms of building height.
- The selected buildings must represent different types of laboratory hazards, functional uses, or facility management approaches for appropriate generalisation.

All case study samples were selected from Chulalongkorn University as most of its laboratory buildings met the selection criteria and provided essential information for the analysis. Being the oldest institute of higher education, and situated in a high-density urban context of Bangkok, the university offered valuable insights for the research.

As shown in Figure 5, a total of 17 laboratory buildings with safety inspection reports were considered. These buildings ranged in age from 4 to 63 years, and had heights ranging from 4 to 20 storeys. Of these buildings, 12 are classified as high-rise buildings; they were grouped into three categories: 4 buildings with elevations ranging from 7 to 9 storeys, four buildings with heights ranging from 12 to 15 storeys, and four buildings with heights ranging from 19 to 20 storeys. Finally, the four tallest laboratory buildings built between 1996 and 2018 were selected as case studies as they comprised the best representatives for this research.

Figure 4

Research Framework

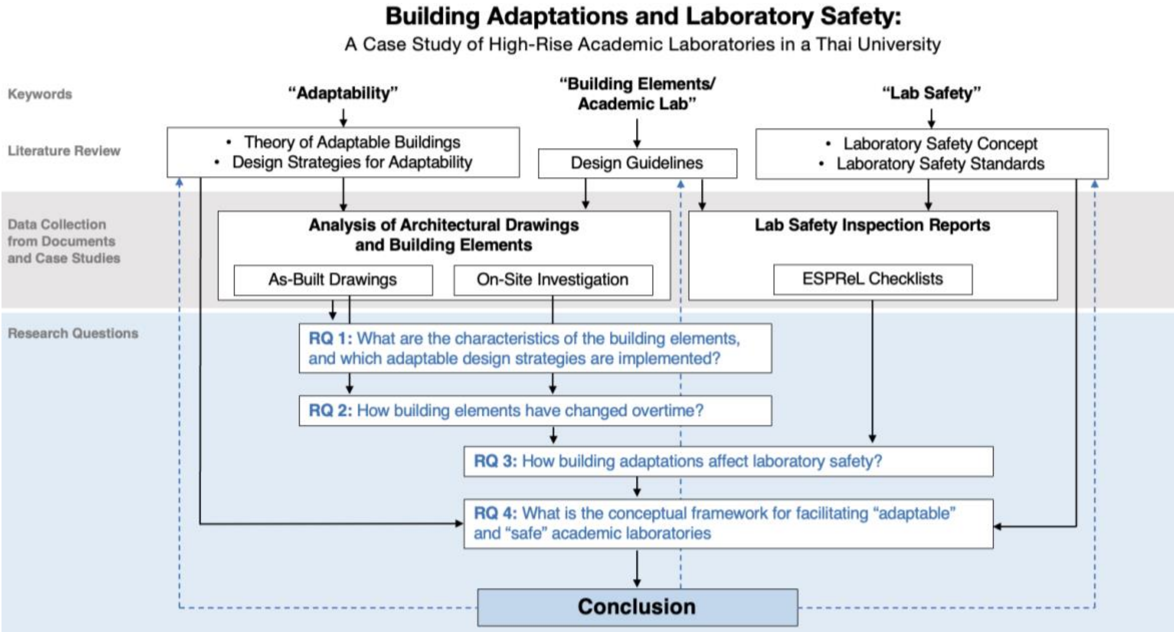
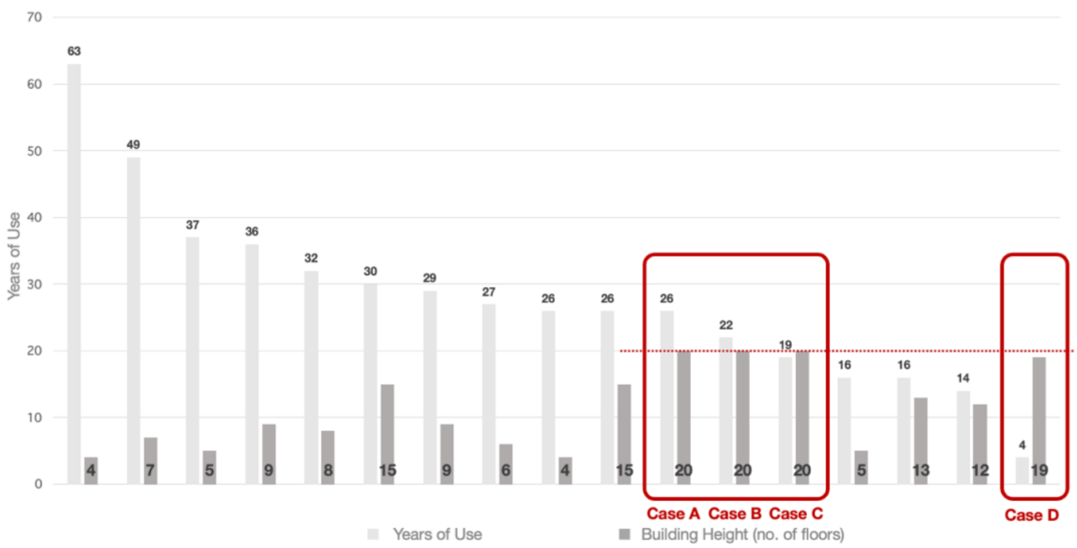


Figure 5

Case Study Selection



Note. This figure illustrates the process of selecting four case studies from a population of 17 laboratory buildings at Chulalongkorn University. The university's laboratories with safety inspection reports are arranged chronologically from oldest to newest. The height of each building is represented in dark grey shading. The four selected case studies are highlighted in red.

General information on case studies

This section provides an overview of the case studies and an initial analysis of their building elements, including structure, utilities, space, and furnishings. Table 2 arranges the case studies based on their years of construction, and presents general information such as the total construction area, building height, and functional use. Most case studies are used for teaching and house research laboratories. Notably, Case C has additional functional areas used as medical/analytical laboratories for hospital services.

Regarding programming requirements, the occupants of Cases A, B, and C belong to a single organisation/faculty. Case D was designed for multi-tenant long-term use among various faculties and institutions related to health sciences, presenting a different approach to space utilisation and administration strategy.

A cross-case analysis of building elements categorised into the four main components of laboratory buildings (Ruys, 1990)–structure, utilities, space, and furnishings–is included in the appendix. The distinctive features found in case studies can be summarised as follows:

Structure: Most case studies on laboratory building design feature a regular orthogonal structural grid constructed with concrete frame structural systems that incorporate shear wall structure (Figure 6). However, the arrangement of the structural grids presents different design approaches. For instance, Case A utilises two rectangular-shaped floor plates with the vertical circulation core in the middle. One of the rectangular-shaped floor plates, with a typical span of 12m, is used for offices and lecture rooms, while the portion with a wider structural span of 15m is designated for laboratory space. This integration of structure and spatial configuration results in two large column-free spaces of different widths, with a floor area ranging from 365 to 400 sq.m. Case B presents another design approach by allocating a double-width structural grid of 15x15m at the four corners. This design approach offers large column-free spaces for teaching laboratories and large lecture rooms. On the other hand, Case C follows a typical centralised core found in standard office tower floor plans. When considering the floor structural systems used in these case studies, only Case D utilises post-tensioned structural systems, while others utilise the system of slabs on beams.

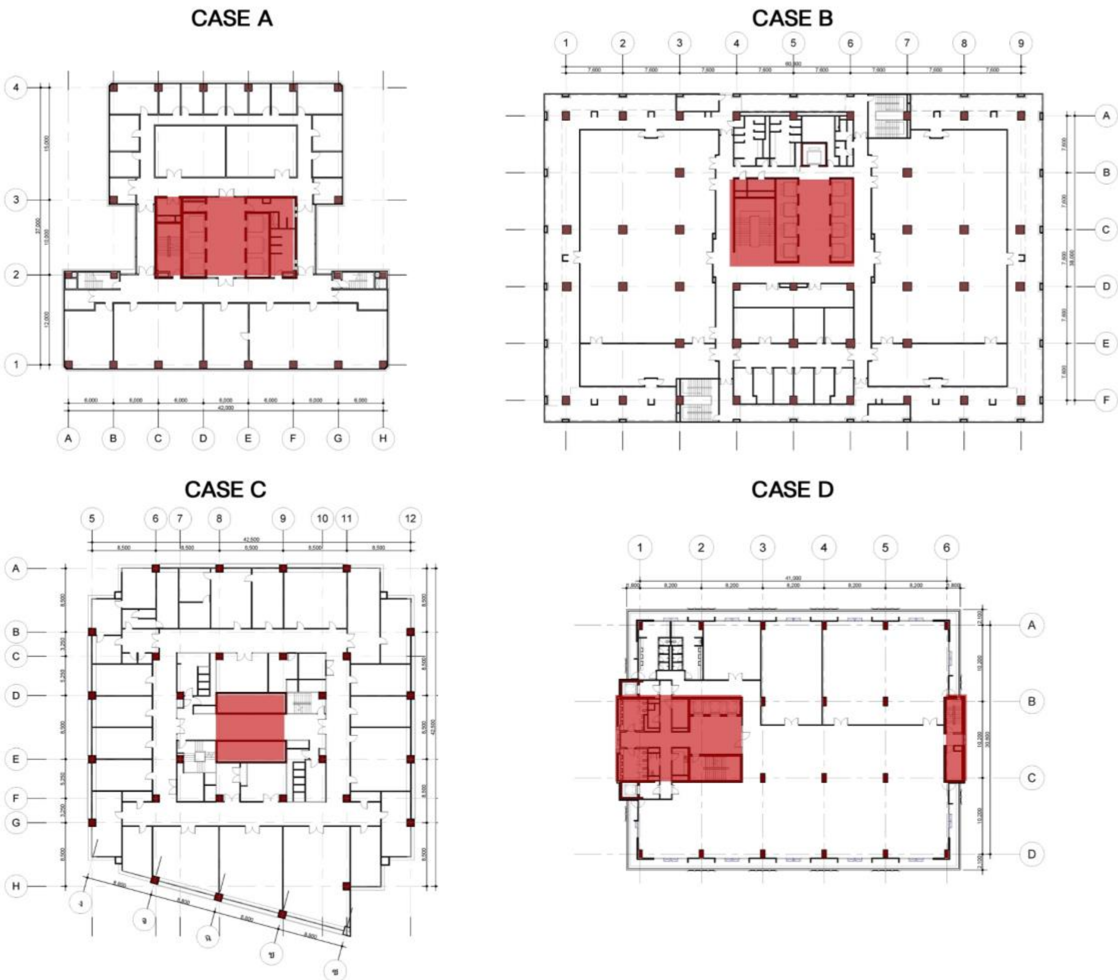
Table 2

General Information of Case Studies

	Case A	**Case B**	**Case C**	**Case D**
Year built (yrs of use)	• 1996 (27 yrs)	• 2000 (23 yrs)	• 2003 (20 yrs)	• 2018 (5 yrs)
Building area	• 28,174 sq.m.	• 51,014 sq.m.	• 50,128 sq.m.	• 28,775 sq.m.
Height	• 20 Floors	• 20 Floors	• 20 Floors	• 19 Floors
Owner/ Functional use	• Faculty of Engineering • Labs/Classrooms/ Office	• Faculty of Science • Labs/Classrooms/ Office	• Faculty of Medicine • Labs/Classrooms/Office/ Hospital service units	• Central Facility for Health Sciences Faculties • Labs/Office/Empty floor for rent
Types of lab hazards	• Physical hazards	• Chemical hazards	• Chemical and biological hazards	• Chemical and biological hazards

Figure 6

The Building Structure of Case Studies



Note. This figure compares typical floor plans from four case studies, all provided at the same drawing scale. The building structures are highlighted in red.

Utilities: The main utility shafts in laboratory buildings are typically located at the vertical circulation core for distribution of building services. However, two different design approaches are found in the case studies: the use of building corner areas (Cases A and C) and the utilisation of balcony space (Cases B and D) along the building facades for HVAC systems and chemical wastewater ductwork (Figure 7).

The case studies feature two types of HVAC systems: centralised air conditioning systems with a chiller, and decentralised split-type systems. While most cases have electricity generators installed for emergency use, only Cases B and D have chemical wastewater treatment systems and predetermined locations for laboratory safety devices.

Figure 7

Design Strategies for Distributing Building Systems on the External Envelope and Using Balcony Space for HVAC Systems.

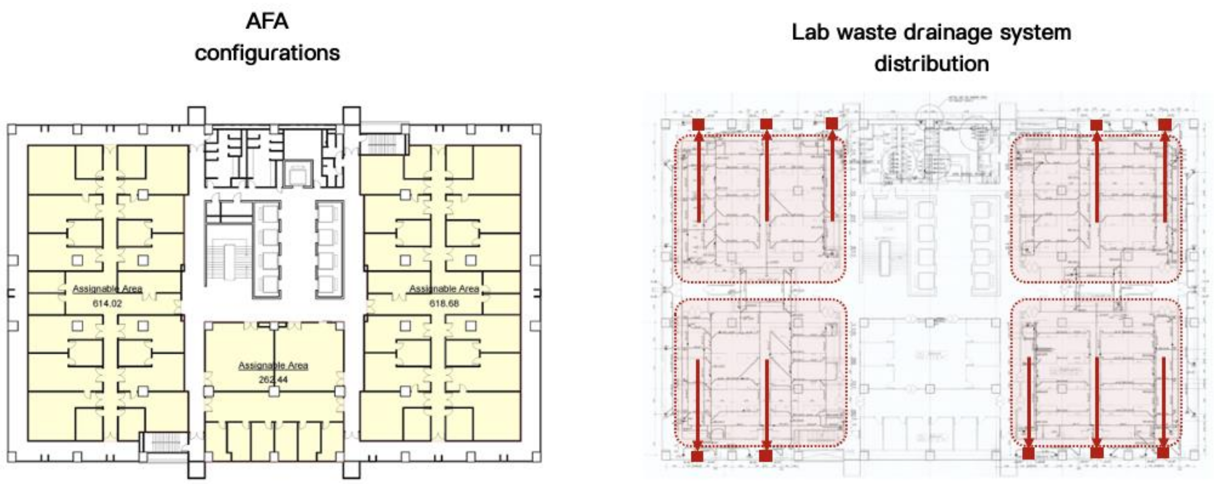
Note. This figure highlights the similarities in design strategies between Case B and Case D, specifically in the distribution of building systems on the external envelope and utilisation of balcony space for HVAC systems.

Space: Case B has the largest assignable floor area (AFA), which can be divided into three zones, consisting of two larger zones of 615 sq.m. and one smaller zone of 262 sq.m. (Figure 8). These zones can be connected via a double-corridor or racetrack system. In contrast, Case A features the largest column-free spaces among the case studies (15x30m.), resulting from the structural and spatial configuration mentioned earlier. Case C offers a shallow depth of floor plans from the building facade, which allows the incorporation of natural lighting into the spaces. However, the primary circulation system is restricted to a single-corridor type. In Case D, the AFA can be rearranged to utilise the entire floor as one laboratory department, or it can be divided into two equal portions with adequate access to the main circulation and evacuation routes. The balcony space on the buildings' envelope of Cases B and D also provides areas for building utilities and maintenance access. The laboratory modules, in all cases, comply with the minimum dimensions required for safety, as stipulated in the laboratory design guidelines.

Furnishings: The location of laboratory sinks was predetermined, except for Case A. However, on-site investigations revealed that fixed workbenches were not predetermined during the design phase. Regarding laboratory safety devices, emergency safety showers were only provided in Cases B and D in the main corridor area for shared use among the units on the same floor. Case C had a distinctive design approach for controlling chemical hazards by predetermining high-risk areas for chemical fume hoods at the four corners of the building (Figure 9), where the equipment could be directly connected to the chemical exhaust ventilation shaft. Finally, regarding interior space partitioning, Cases B and D utilised light-frame wall systems for ease of reconfiguration, while the others used typical masonry walls.

Figure 8

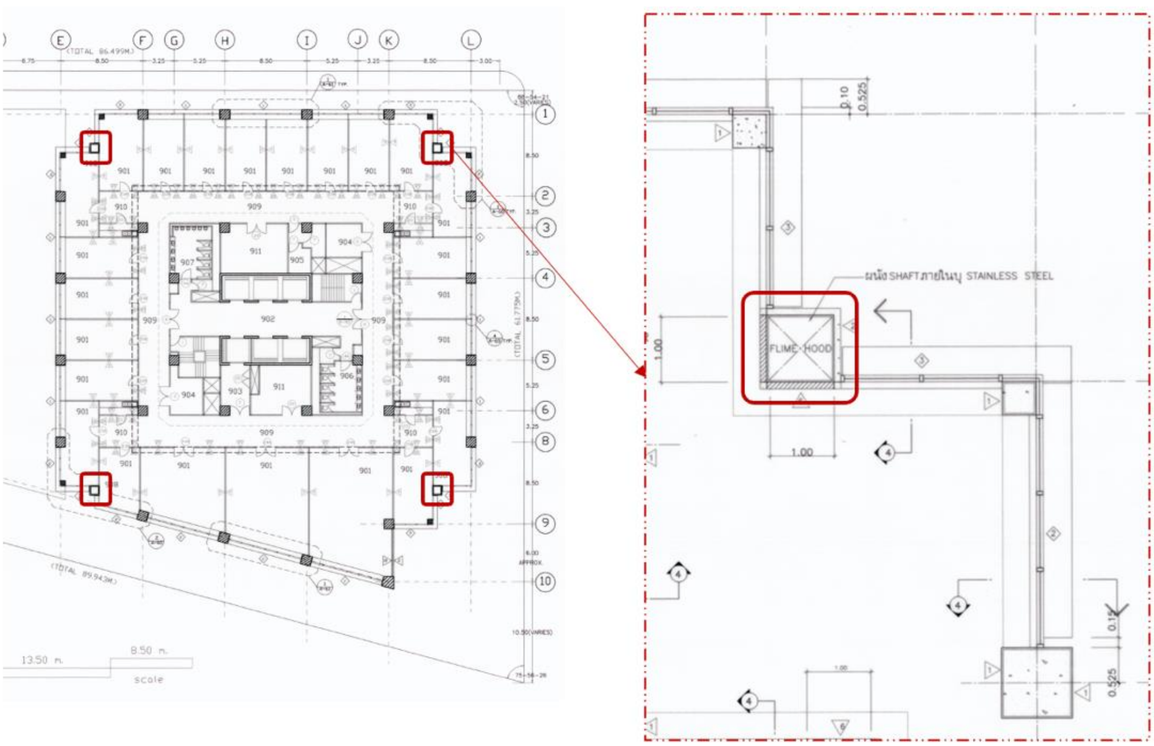
Assignable Floor Area (AFA.) Configurations and the Distribution System of Lab Waste Drainage System in Case B



Note. (Left) This figure illustrates the design strategies employed to divide the assignable floor area (AFA) into a small portion for offices and two larger portions for labs, with all areas having access to the main circulation. (Right) The figure shows the laboratory waste drainage system distributed on the external facade, allowing for use by laboratories in both wings as well as further division of lab space into north and south portions.

Figure 9

Design Features for Chemical Exhaust Ventilation System in Case C



Note. This figure illustrates the design strategies for chemical exhaust ventilation as depicted in the original drawings of Case C.

RESULTS AND DISCUSSION

Adaptable design strategies in high-rise laboratory buildings

Through comprehensive investigation of building elements and drawings, this analysis reveals that adaptable design enablers have been implemented in the design of high-rise academic laboratory buildings. Although the four case studies were built at different times between 1996 and 2018, adaptable design strategies were found in all cases, with variations. Two commonly found strategies were "Long-life" and "Loose-fit."

Table 3 presents a summary of the adaptable design strategies observed in the case studies. Regarding "Long-life" strategies, most cases overdesigned the structural capacity and used concrete as the primary structural material, resulting in durable and low maintenance construction. "Loose-fit" strategies were also prevalent, with simple rectangular floor plans, regular structural grids, and light frame walls as interior partitions.

However, the strategies of "Layer separation" and "Reducing uncertainty" were not widely utilised. Only Case B and Case D incorporated designs intended to separate laboratory utility systems from the general building systems. The distribution of laboratory utilities along the buildings' external envelope and the provision of balcony space allowed for modification and expansion of laboratory utilities, such as chemical waste drainage, HVAC systems, and maintenance access.

Adaptations of academic laboratory buildings

Table 4 summarises the adaptations to building elements in each case study, categorised by the "Building Layers" model (Brand, 1995). The details of the adaptations for each building layer are described below.

Site: The site component remains unchanged in all case studies, while the surrounding area has undergone continuous development as part of the university campus masterplan. For example, Case A encountered the limitation of open space due to the construction of a high-rise building to the north within a few years of its completion. On the other hand, Case C has had open space within its boundary, which is sufficient for building an additional chemical waste storage and chemical wastewater treatment plant to improve laboratory safety.

Structure: The structure component has undergone more significant modifications in some cases, such as Case A, where the typical floor plates were expanded beyond the fire staircase shear wall to create emergency evacuation routes and balcony space for CDU placement (Figure 10). Other cases have undergone minor structural additions, such as installing a steel mezzanine for extra storage space.

Skin: The building envelope adaptations have been primarily due to changes in HVAC requirements. Additional supply and exhaust ventilation ductwork has been installed, which has penetrated the skin layer of the buildings. However, Case C presents difficulties in accommodating additional HVAC requirements (Figure 11) as the exterior envelope module consists of modular precast concrete panels with glazed curtain walls on the upper part. Consequently, some additional split-type CDUs are located near the exhaust ventilation shaft, and share the exhaust duct through mechanical ventilation of the fire staircase at the central core. On the other hand, case studies with balcony space (Case B and D) present no issues in this regard, as the balcony spaces can be used for installation of HVAC systems, and provide access for maintenance.

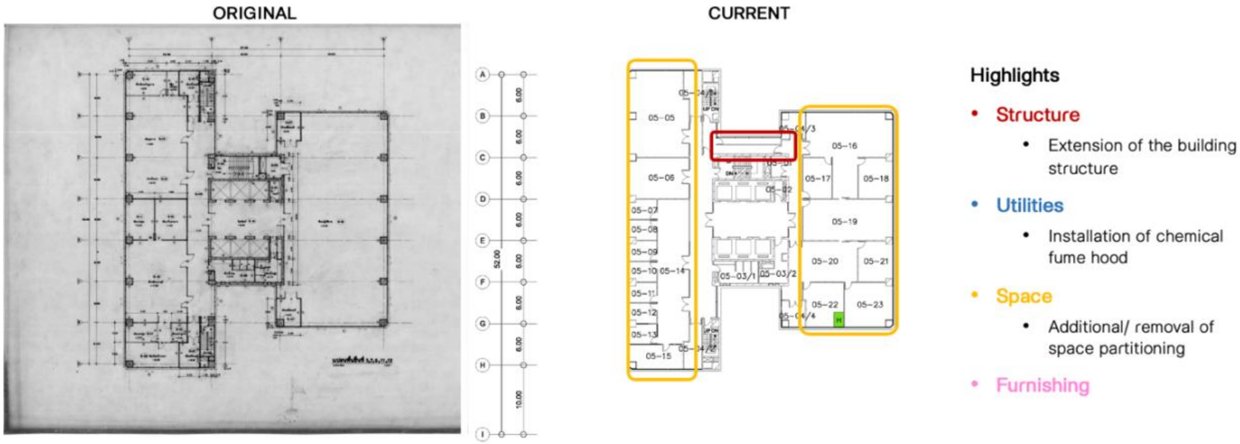
Table 3

Summary of Adaptable Design Strategies Observed in Academic Laboratory Buildings

Strategies	Findings
Long-Life	• Most buildings are designed with **reserved structural capacity.** • **The shear wall and concrete frame are the most common structural system.** • **Two types of floor structures can be found: (1) slab on beams and (2) post-tensioned.** The post-tensioned structure can save floor-to-floor height; however, the structure is less viable and could cause difficulties in laboratory renovation (i.e., laboratory sinks and waste drainage system relocation, which requires coring through the slab). • **Two approaches on architectural finishes selection**, including (1) Masonry/RC walls with smooth plaster painted finishes, and (2) facade cladding (i.e., mosaic tiles). The latter can be more problematic in long-term use, as the adhesives deteriorate, resulting in the cladding materials falling off. Therefore, material specifications, technical installation details, and proper maintenance must be carefully considered.
Loose-Fit	• **Simple rectangular structural grids** with regular spans from 6 to 15 m. are common. • By integrating structural systems and spatial utilisation, ample **column-free space can be allocated (i.e., 15x30m., 15x15m.).** • **The floor plate sizes range from 1,250 to 2,417 sq.m.** with the **AFA designed for accommodating spatial utilisation of various sizes** and access to main vertical circulations. All case study can accommodate extensive open-plan teaching and small module research labs. • **Lightweight frame walls** are used for interior partitioning in some case studies.
Layer Separation	• **In most cases, spaces are partitioned by modular systems. The dimensions of all modules comply with the standard laboratory modules.** • **Balcony space can be provided for building services** (i.e., CDUs). Moreover, connecting the area with the main corridor can provide better accessibility for maintenance and services of the building systems and facades. • **The main distribution of utilities is mainly aligned with the central vertical core structure of the buildings. The utility shafts for fume hood exhaust and waste drainage are along the exterior facades.**
Reduce Uncertainty	• All case studies have original as-built drawings; however, there is a **lack of accurate lab furniture and equipment plans, and existing condition and maintenance records.** • Common building components include precast concrete panels of exterior facades, shading devices, and building components for vertical shafts along the exterior facade. • Providing **access from the main corridor to the utility system**, such as AHU and EE rooms, allows ease of maintenance. • **No interstitial floors provided**

Figure 10

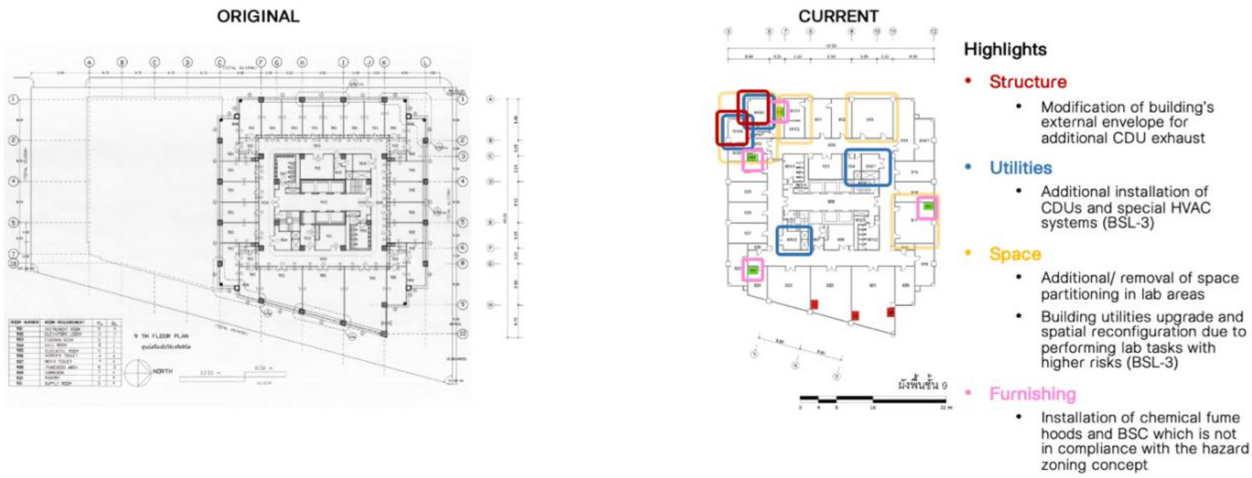
Analysis of Building Adaptations of Case A



Note. This figure illustrates the analysis of building adaptations in Case A, highlighting the extension of the building's structure. This adaptation not only enhances fire evacuation routes but also provides extra balcony space to accommodate additional HVAC systems.

Figure 11

Analysis of Building Adaptations of Case C



Note. This figure depicts the analysis of building adaptations in Case C, demonstrating changes made to various building elements. The figure highlights the interdependence between building layers, such as the modifications made to utilities, space planning, and external envelope in response to evolving functional needs.

Service: The building services layers have undergone significant adaptations, particularly in relation to HVAC systems, sanitary and environmental engineering, and emergency and communication systems. Cases A and C have both undergone transitions from centralised to decentralised HVAC systems, likely due to changes in laboratory work and space requirements. These changes have resulted in modifications to the buildings' skin layers to accommodate the unplanned exhaust air ductwork (Figure 12). Additionally, common adaptations have also included adding or relocating laboratory sinks or emergency showers.

A flexible building structure and distribution of main utilities are necessary to facilitate such adaptations. For example, Cases B and D present design strategies that involved distributing utility supply and waste drainage systems along the building envelopes to provide unobstructed floor plans that enable flexibility in rearranging the laboratory layouts. However, in Case D, the post-tensioned floor structures pose a significant challenge to adapting building services since altering this structural system is more complex than modifying a simple slab on beams. This highlights the need to prioritise the flexibility of the structural layer.

Space plan: The space plan layer involves the reconfiguration of spaces. Most case studies have shown a tendency to expand or reconfigure laboratory units or department spaces beyond the assignable floor area (AFA), resulting in the discontinuation of fire evacuation routes or limited access to building systems maintenance. However, the reconfiguration of individual laboratory units often involves compartmentalising larger spaces into smaller units, which may be intended to segregate different laboratory tasks or enhance hazard containment as required by lab safety regulations. Additional adaptable design strategies observed in Cases B and D included space partitioning with light-frame walls and leaving some floor areas "unfinished" for future renovation by tenants.

Stuff: Surprisingly, none of the case studies includes as-built interior drawings. As-built drawings of Cases A and D provide only the main risers and drainage systems, with an "unfinished" or "undetermined" floor layout design. On the other hand, drawings for Cases B and C include interior space partitioning of laboratory modules and laboratory sinks. When comparing the existing conditions with the as-built architectural and sanitary engineering drawings, most building adaptations have involved adding or relocating space partitions, laboratory sinks, or safety equipment. Regarding laboratory safety equipment, the location of chemical fume hoods is not predetermined in any case, which necessitates modifications to the HVAC systems during the occupancy phase. A distinctive design strategy is evident in Case C, where the main exhaust ventilation shafts are provided at building corners, intended for convenient plug-in installation of additional chemical fume hoods. However, on-site observation has exposed the feature's lack of maintenance, resulting in it currently being adapted to serve as exhaust ventilation shafts for additional CDUs of the split-type HVAC system.

Figure 12

Modification of Building’s Skin Layer Due to HVAC Requirements in Case C

Note. (Left) This figure illustrates the additional installation of CDUs in one lab unit of Case C, leading to an inappropriate adaptation in terms of space utilisation and the building's skin layer. (Right) This figure highlights various random building adaptations in the skin layer resulting from changes in HVAC requirements.

Table 4

Building Adaptations of Laboratory Buildings Categorised Into Brands" (1995) "Shearing Layer"

	Case A	Case B	Case C	Case D
Site	• No major changes	• No major changes	• The vacant site area was utilised to construct additional building structure	• No major changes
Structure	• Floor plate extension with balcony space on typical floors to enhance fire safety evacuation route	• No major changes	• No major changes	• No major changes
Skin	• Facade modification to accommodate additional HVAC systems	• No major changes	• Facade modification to accommodate additional HVAC systems	• No major changes
Service	• Additional installation of lab waste drainage at main shafts within the building • Additional installation and replacement of HVAC and CDUs	• Additional installation of vertical risers and ductwork integrated with the exterior facade • Additional installation and replacement of HVAC and CDUs in the balcony space	• Additional vertical risers and ductwork installation at main shafts within the building • Additional installation of split-type A/C with other advanced HVAC systems as replacement of existing centralised A/C systems due to BSL-3 requirements. • Additional construction of chemical wastewater treatment plant	• Additional installation of vertical risers and ductwork integrated with the exterior facade • Addition installation of HVAC and CDUs in the balcony space
Space	• Reconfiguration of space partitioning and expansion of departmental/lab area out of AFA	• Reconfiguration of space partitioning within the AFA	• Reconfiguration of space partitioning and expansion of departmental/lab area out of AFA • Area expansion for lab support/services	• Addition of space partitions by tenants
Stuff	• Additional installation of lab furniture and sinks	• Addition and relocation of sinks, fume hoods and ER showers	• Additional installation of fume hoods, BSC, and emergency showers	• Addition of lab furniture, sinks, fume hoods and emergency showers

Safety concerns in laboratory buildings

As shown in Table 5, the examination of ESPReL safety inspection reports indicated that three out of four case studies had primary laboratory safety concerns regarding sanitary and environmental engineering, HVAC systems, and emergency response and communication systems. The following section summarises major laboratory safety problems and analyses their relationship with building adaptations.

Regarding sanitary and environmental engineering systems, most case studies encountered issues related to water leakages, inadequate wastewater treatment systems, and a lack of regular maintenance. Water leakage problems were attributed to improper installation and deterioration of the piping systems from the lack of maintenance. However, the inadequate wastewater treatment systems resulted from deficiencies in the original design, which did not account for changes in laboratory usage that involved handling more hazardous materials than initially planned.

Concerning HVAC systems, common safety problems included inadequate ventilation, improper installation and location of HVAC systems, and a lack of inspection and maintenance. These issues may have resulted from misalignment between the original design strategies and actual building adaptations, particularly in the layers of "space plan" and "service." The safety inspection report of Case C also revealed several issues, including high humidity and mould growth due to air condensation, particularly in underground levels or the area adjacent to spaces that required 24-hour air-conditioning.

Safety problems in emergency and communication systems were mainly related to unsafe fire evacuation routes and malfunctioning fire protection and emergency communication systems. In most cases, unsafe fire evacuation routes were caused by reconfiguring or expanding functional areas outside the designated AFA or by unsafe storage practices leading to overflowing items from storage areas into circulation corridors (Figure 13). Laboratory users should consider safety in a broader sense, especially before planning building adaptations, where security should be a consideration not only at the current time or in the laboratory premises but also in the public area throughout the building, and in a long-term manner. This suggests the need for improving facility management control regarding space utilisation, and greater user safety awareness.

The relationship between building adaptations and laboratory safety

The analysis reveals that safety concerns in laboratory buildings can be attributed to three interrelated aspects: (1) the original design of the building, (2) building adaptations, and (3) use and maintenance. Safety concerns can arise from any of these aspects individually or in combination. Table 6 summarises samples of 12 checklist items related to architecture from a total of 48 items in the ESPReL checklist.

Table 5

Percentage of Items Compliant with ESPReL Checklist

	ESPReL Checklist: Physical characteristics of laboratory, equipment, and tools (48 items)	Case A	Case B	Case C	Case D
1	Architecture (12 items)	50%	67%	17%	33%
2	Interior Architecture: Furniture, Tools, and Equipment (6 items)	50%	50%	50%	67%
3	Structural Engineering (4 items)	75%	75%	75%	100%
4	Electrical Engineering (10 items)	60%	60%	40%	60%
5	Sanitary and Environment Engineering (3 items)	0%	33%	0%	100%
6	Heating Ventilation and Air-Conditioning Engineering (HVAC) (4 items)	25%	25%	0%	100%
7	Emergency Response and Communication System (9 items)	11%	33%	11%	56%

Figure 13

Unsafe Fire Evacuation Routes and Obstructed Main Corridor

Note. These figures depict safety issues related to unsafe fire evacuation routes observed in multiple cases, primarily caused by the overflow of stored items from storage areas into the circulation corridor. The left figure showcases the unsafe spatial utilisation of the balcony space in Case B, while the right figure highlights the blockage in the fireman's lift lobby of Case C, caused by unsafe storage practices.

Table 6

Analysis of Safety Problems in Laboratory Buildings–Architecture Section of the ESPReL Checklist

	ESPReL Checklist: Laboratories, Equipment and Tools	Case Studies				Cause of Safety Problems		
	Architecture	**Case A**	**Case B**	**Case C**	**Case D**	**Original Design**	**Building Adaptations**	**Use and Maintenance**
1	**Are the inside and outside environments free from any potential hazards or sources of harm?**							
	• There is a large number of stored items blocking pathways and posing a risk due to their heavy weight and flammable nature.		X					O
	• Safety equipment is installed in high-risk areas.			X			O	O
	• There are operational practices that pose a risk of accidents.			X				O
	• The ceiling has cracks, and the exterior wall material is damaged, posing a risk of collapse.			X		O		O
	• Additional rooms or mezzanine floors have been added, increasing the risk in case of emergencies.	X		X		O	O	
	• There is no designated waste storage area on each floor.	X			X	O		
	• Aluminum sunshade panels are falling off from their installation positions.				X	O		
2	**Does the laboratory have a clear separation between laboratory space and non-laboratory areas?**							
	• Non-related items are found stored together without proper segregation.	X		X	X			O
	• Non-separation between laboratory and researchers' rest area.	X		X	X	O	O	O
	• Modifications to the space have been made for activities unrelated to laboratory operations.	X		X			O	O

Table 6 (Continued)

	ESPReL Checklist: Laboratories, Equipment and Tools	**Case Studies**				**Cause of Safety Problems**		
	Architecture	**Case A**	**Case B**	**Case C**	**Case D**	**Original Design**	**Building Adaptations**	**Use and Maintenance**
3	**Are the space and ceiling height of the laboratory rooms and other rooms suitable for the operations, number of operators, and the types and quantity of equipment and tools used?**							
	• There is an excessive amount of tools and equipment that exceeds the room's capacity to accommodate them properly.			X		O	O	O
4	**Are the floor, wall, and ceiling surfaces made from appropriate materials for the laboratory's operations, and are they regularly maintained?**							
	• Damage from rainwater leakage; materials broken, cracked, and deteriorated.	X	X	X	X	O		O
	• Dirty and damaged from the accumulation of chemical residues and lack of maintenance.	X	X	X				O
	• Mold accumulation.			X		O		O
5	**Does the laboratory provide doors and windows of suitable size and quantity, allowing controlled access and easy opening in case of emergencies?**							
	• Materials and equipment are blocking pathways and restricting access.	X		X	X			O
	• The doors do not have a twist-lock system for emergency exits.				X	O		
6	**Are vision panels installed on the doors to improve visibility and safety?**							
	• The doors are solid panels (without vision panels)	X			X	O		
	• The vision panels on the doors are covered or modified in a way that obstructs visibility.			X	X		O	O

Table 6 (Continued)

	ESPReL Checklist: Laboratories, Equipment and Tools	Case Studies				Cause of Safety Problems		
	Architectur	**Case A**	**Case B**	**Case C**	**Case D**	**Original Design**	**Building Adaptations**	**Use and Maintenance**
7	**Do the windows in the laboratory allow for ventilation, have locking mechanisms, and are they easily opened in case of emergencies?**							
	• No safety issues were identified	-	-	-	-	-	-	-
8	**Are the clearance widths in general corridors at least 0.6 meters and at least 1.50 meters in indoor walkways?**							
	• Obstructions of the pathway resulting in inadequate width.	X						O
9	**Are the corridors and areas adjacent to the entrance hall free from obstructions, allowing unimpeded movement and clear emergency access?**							
	• Placement of a water-absorbent mat from the refrigerator poses a risk of accidents on the main traffic pathway.			X				O
	• Obstructions of the corridor from appliances and furniture.	X	X	X	X			O
10	**Is the exit pathway free from danger areas and any equipment that may pose risks, such as chemical storage cabinets or hoods?**							
	• Obstructions of the pathway.	X	X	X	X			O
	• Exit pathways passing through hazardous appliances and chemical storage areas.		X	X	X			O
11	**Is there a separate passage way for the laboratory from the main passage of the building?**							
	• No safety issues were identified.	-	-	-	-	-	-	-

Table 6 (Continued)

	ESPReL Checklist: Laboratories, Equipment and Tools	**Case Studies**				**Cause of Safety Problems**		
	Architecture	**Case A**	**Case B**	**Case C**	**Case D**	**Original Design**	**Building Adaptations**	**Use and Maintenance**
12	**Does the laboratory provide area and interior information, including a floor plan, current locations, fire escape routes, and emergency equipment locations?**							
	• Incomplete floor plan information.			X	X			O

Note. In this table, the ESPReL checklist items are highlighted in green. The bullet points beneath each item describe the specific details of safety problems identified in each case study. The "X" represents safety problems that were identified, and the "O" represents the related causes. For a comprehensive analysis of all items, please refer to Appendix 2

Safety concerns often arise when the original design is not suitable for functional use or when adaptations become excessively challenging; examples include safety concerns regarding inadequate HVAC and exhaust systems resulting from changes in laboratory works, or the absence of chemical and biological wastewater treatment systems in the original design of the building. Since safety requirements in laboratories are dynamic and laboratory work continuously evolves, integrating adaptable design strategies into a building's design is the key to enhancing its capacity to adapt to changing safety needs over time.

Building adaptations can also lead to apprehensions about safety when the actual adaptations deviate from the initially planned adaptable design strategies. For example, safety concerns may arise from lack of separation between laboratory and non-laboratory areas due to uncontrolled space partitioning or user adaptations. Additionally, obstruction of exit routes may occur from additional space partitioning beyond the assignable floor area (AFA). Correctly understanding the original design and integrating adaptable design strategies are crucial in avoiding these types of issues.

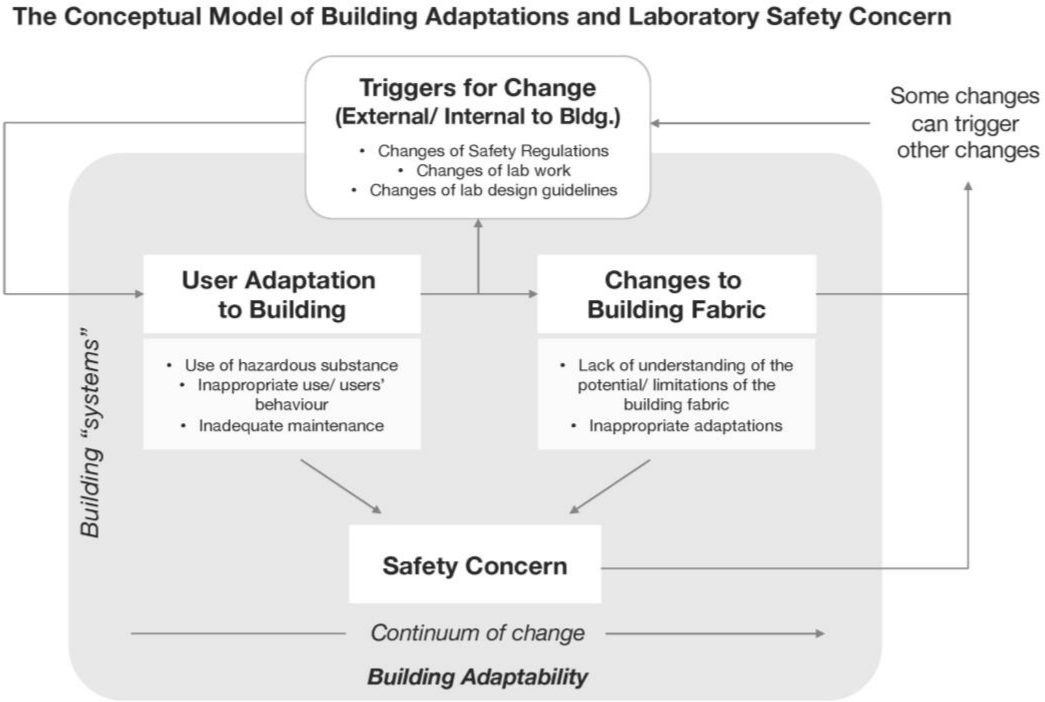
Lastly, inappropriate building use and inadequate maintenance are among the most common causes of safety concerns in laboratory buildings. Inappropriate building use may involve the excessive storage of items or hazardous substances, or obstructing corridors and emergency egress routes, leading to inadequate corridor width. This illustrates that safety concerns can arise even when the building was originally designed with safety in mind. Similarly, lack of maintenance can accelerate the deterioration of physical elements, posing safety risks in both old and newly built laboratory buildings. This underscores the significance of design strategies that facilitate convenient access for maintenance, and improved administrative controls over building use and adaptations to ensure safety.

The conceptual framework

The conceptual framework for adaptability and safety, depicted in Figure 14, is an extension of the "Conceptual Model of Change and Building Adaptability" (Kamara et al., 2020), with the incorporation of the safety aspect. This framework enhances our understanding of the relationship between adaptations and safety

Figure 14

The Conceptual Model of Building Adaptations and Laboratory Safety Concern



concerns throughout the life cycle of academic laboratory buildings.

When external or internal factors trigger changes, adaptations become necessary, which can lead to safety concerns that arise from inappropriate user adaptations or modifications to the building fabric. The safety concerns of the laboratory can then act as triggers for further changes, creating an iterative process.

The findings of this paper highlight that inappropriate user adaptations mainly involve the use of hazardous substances beyond engineering control limits, improper utilisation of functional areas, and inadequate maintenance practices. Similarly, inappropriate adaptations to the building fabric often result from a lack of understanding regarding the potential or limitations of the building's adaptability, coupled with inadequate safety awareness during the adaptation process.

However, the integration of adaptable design strategies (Black et al., 2019; Ross et al., 2016; Schmidt III & Austin, 2016) with the consideration of interfaces between each building layer (Brand, 1995) during the original building design plays a crucial role in facilitating ease of adaptation for both users and building fabric over time. This aspect significantly contributes to our existing knowledge, demonstrating that building adaptability not only mitigates obsolescence but also enhances safety throughout the building's usage, particularly when safety concerns are of primary focus.

Practical applications

Table 7 presents the practical implementation of this research. The findings from this study can be utilised to identify potential design considerations for high-rise academic laboratory buildings. These considerations can then inform the planning of adaptations for existing buildings, and be integrated into feedback related to refining adaptable design strategies for future facilities. Ultimately, the proposed framework can assist stakeholders, laboratory users, and design professionals in understanding the relationships between adaptations and safety, facilitating effective planning, design, management, and execution of building adaptations to accommodate changing functional requirements and safety regulations.

Table 7

Practical Implementation of Research Findings

Layers	Building adaptations	Safety concerns	Possible design considerations/ Design strategies
Site	• Utilisation of the vacant site area to construct additional building structure	• *Fire safety and emergency systems:* ○ Compromised safety due to building setback space being occupied	• Reserve extra site space for the additional construction of building systems relating to safety, and provide alternative scenarios to manage compromised safety
Structure	• Floor plate extension with balcony space on typical floors to enhance fire safety evacuation routes	• *Structural systems*: ○ Increased structural load and modification to structural systems	• Reserve structural load capacity/Utilise durable materials • Utilise simple and viable structural systems • Provide standardised structural components and connections with ease of modification
Skin	• Facade modification to accommodate additional HVAC systems • Additional installation of ductwork integrated with the exterior facade	• *Architecture and interior design:* ○ Inappropriate installation/modification of building facades and deterioration of building materials • *HVAC systems:* ○ Inadequate and improper exhaust ventilation	• Consider integrating the concepts of safety, durability, accessibility, serviceability, and flexibility into the architectural design of the building skin (i.e., utilising cantilevered slabs/balcony space to accommodate additional building systems and provide access for maintenance)

Table 7 (Continued)

Layers	Building adaptations	Safety concerns	Possible design considerations/ Design strategies
Service	• Additional construction or installation of building systems/utilities relating to chemical waste • Additional installation of lab waste drainage at main shafts within the building or integrated with the exterior facade for the building with balcony space • Additional installation or replacement of HVAC systems due to spatial reconfiguration and special lab requirements (i.e., BSL-3)	• *Sanitary systems:* ○ Inadequate chemical wastewater treatment systems and inappropriate/substandard installation of chemical waste drainage systems • *HVAC systems:* ○ Insufficient ventilation and conflicts between centralised HVAC systems and specific HVAC requirements of each lab within the same floor • *Fire safety and emergency systems:* ○ Insufficient fire and lab safety emergency devices with a lack of maintenance	• Provide redundant space for additional building systems with access to regular maintenance and upgrades (i.e., interstitial space) • Consider lab ventilation, HVAC system, fire sprinkler systems, lab safety devices, and spatial reconfiguration of lab modules • Consider separating the service layers with a high frequency of changes (HVAC, Chemical waste drainage) from other layers and provide access for ease of maintenance (i.e., locating and distributing HVAC systems and utility ductwork at the outer layer of the building envelope)
Space	• Reconfiguration of space partitioning and departmental/lab area expansion out of AFA • Change in functional use in some spaces. • Addition of space partitions by tenants and increasing trend of dividing space into smaller lab units	• *Fire safety and emergency systems:* ○ Excessive storage of chemical hazards and lab equipment in lab units and public areas blocking evacuation routes ○ Complex space partitioning resulting in fire safety concerns	• Consider the appropriate level of "spatial specificity" • Provide a clear functional space and AFA allocation strategies that enable flexibility in spatial reconfigurations into small and large lab units with adequate security and access, not compromising fire safety regulations
Stuff	• Additional installation/ relocation of lab furniture, sinks, equipment, and emergency lab safety devices	• *Architecture and Interior Design:* ○ Inappropriate installation location of chemical fume hoods and emergency lab safety devices	• The "Hazard zoning concept" should be prioritised and applied to space planning and actual building use • The predetermination of possible sink locations and special lab safety equipment is recommended

Note. This table provides a summary of potential design considerations derived from the research, emphasising the relationship between building adaptations and safety concerns in laboratory buildings.

CONCLUSION

In conclusion, this research investigates adaptable design strategies, building adaptations, and their relationships to laboratory safety in high-rise academic laboratory buildings.

The analysis of empirical evidence reveals that adaptable design strategies are similar to those found in high-rise office buildings have already been implemented in laboratory buildings, with a particular emphasis on the "long life" and "loose fit" concepts. However, laboratory buildings require a distinct approach to adaptation due to the dynamic nature of laboratory tasks and the critical role of engineering controls in ensuring laboratory safety.

In terms of building adaptations, the analysis reveals significant transformations that have occurred in building services, including HVAC systems, sanitary and environmental engineering, and emergency systems. Consequently, the investigation emphasises the importance of incorporating the concept of building layer separation and ensuring accessibility for maintenance purposes. Therefore, adaptable design strategies for laboratory buildings should prioritise the separation of building layers, with particular attention to the "services" layer, and consider the interrelated layers, including the "space" and "skin" layers, to facilitate easier adaptation and safety upgrades.

Nevertheless, the investigation also reveals that many adaptations deviate from the intent originally incorporated into the design, leading to safety problems across multiple aspects. Furthermore, the absence of stringent administrative control or effective facility management strategies exacerbates these safety issues, highlighting the critical need for comprehensive measures to mitigate the risks associated with building adaptations.

To address these challenges, the study proposes the use of "Conceptual Model of Building Adaptations and Laboratory Safety Concern," which integrates the concepts of laboratory safety and adaptable architecture. The conceptual framework emphasises the importance of incorporating safety considerations throughout the process of building adaptations and offers valuable insights into the relationships between adaptability and safety.

Viewing laboratory buildings as "shearing layers" enables stakeholders, laboratory users, and design professionals to gain a comprehensive understanding of potential safety concerns as well as the possibilities and limitations of the existing built environment. This facilitates an iterative process of refining appropriate design strategies for newly constructed and renovated academic laboratory facilities, ensuring that safety aligns with rapidly evolving laboratory safety requirements.

The research acknowledges the limitation of inconsistent historical data on adaptations of laboratory units over time. It suggests further investigations that include time-series analyses to examine the patterns of adaptations in each layer of the building components. Additionally, research on facility management strategies to control and maintain appropriate building adaptations and laboratory safety is highly recommended. By providing organised and accurate information about building use, laboratory tasks, and the current condition of safety-related building components, a more comprehensive safety approach can be achieved throughout the lifecycle of laboratory buildings.

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