JOURNAL OF DESIGN FOR RESILIENCE
IN ARCHITECTURE & PLANNING

Research Article
Online: www.drarch.org
Volume 4, Issue 1, (105-121), 2023
DOI: 10.47818/DRArch.2023.v4i1086

Analyzing design and planning trends in medical research laboratories and workplace environments: A benchmarking study

Zahra Zamani*

Abstract

Architects and planners typically rely on past experiences and exclusive methods to determine the allocation of space and planning costs. However, the actual space allocations and physical attributes of laboratory and workplace environments require further exploration, highlighting the need for more research. To address this knowledge gap, this study compared three medical research facilities' architectural, casework, and module properties to identify essential space allocations, physical attributes, and future research directions. The study utilized REVIT models to collect floor plans of three medical research facilities within the last twelve years, with variables of interest including room classification size, Building Gross Footage (BGSF), Departmental Gross Footage (DGSF), laboratory module size, and module quantity per laboratory. Space Syntax analysis was used to compare connectivity measures across the three buildings. The findings demonstrated a trend towards laboratory spaces that maximize collaboration, flexibility, and efficiency while balancing open and private workspaces. Laboratory support spaces per laboratory room increased, potentially due to a demand for greater flexibility and spatial needs. Lab workstations were relocated outside laboratory areas to enhance safety and reduce costs. The analysis also revealed a shift towards smaller lab modules with larger widths to reduce redundancy, support safer distances, reduce travel distances, and increase the number of modules per lab. Furthermore, contemporary lab workspaces had higher connectivity values, indicating a trend towards more connected, collaborative spaces that encourage meetings and spontaneous interactions. This study highlights the importance of continuously evaluating and optimizing laboratory space allocation and design to promote productivity, efficiency, and collaboration in medical research facilities. Future research should conduct longitudinal studies using empirical data to address the limitations of current research.

Keywords: Medical research facilities, laboratory spaces, Benchmarking, module properties, space syntax, efficiency

1. Introduction

Benchmarking is a fundamental process in the industry for assessing products, metrics, and practices against competitors to identify areas of improvement and success (Kahn et al., 2002). This continuous process enables companies to access a broader database of marketplace dimensions and data-driven best practices. However, benchmarking presents challenges, including data quality and time-consuming data gathering due to evolving data systems, definitions, and staff training. Standardized definitions and practical training are necessary for successful and comparable benchmarking efforts. Permission barriers and the fear of losing a competitive advantage in the market have resulted in a reluctance to share benchmarking data in the building industry (Kahn et al., 2002; Kelly & Pingel, 2022). Therefore, addressing these challenges is crucial for effective benchmarking and to facilitate knowledge sharing and collaboration within the industry.

*(Corresponding author) Ph.D., BSA LifeStructures, USA, zzamani@bsalifestructures.com
Article history: Received 10 January 2023, Accepted 14 April 2023, Published 30 April 2023

In laboratory metrics, understanding trends that support diverse work styles, collaboration, comfort, productivity, or privacy needs is necessary. The rapid transformation of science, methodologies, technologies, and the workplace has profoundly affected laboratory metrics. Although a limited number of commonly used key performance indicators exist, research investigating the effects of workplace strategies in the laboratory has produced a new paradigm and a shift in lab design metrics. Social and cognitive factors are significant in innovation and knowledge access, such as face-to-face communication with peers, a valuable metric related to information exchange, individual effectiveness, or team performance (Ancona & Caldwell, 1992; Ancona, 1990). Incorporating these factors into laboratory metrics is crucial for promoting effective knowledge sharing and collaboration within the laboratory setting.

The allocation and organization of laboratory spaces are crucial for ensuring the quality of work and compliance with accreditation processes. The laboratory layout affects traffic patterns, workflow, safety, and functionality outcomes, making it essential for planners, designers, and facility managers to consider benchmarking lab design for optimal work procedures, workflow, collaboration, and staff productivity. An optimized laboratory space can yield a better return on investment for Science and Technology (S&T) organizations. Renovating laboratories to cater to different scientific disciplines or research types can be expensive. It may not be possible for smaller projects with limited budgets to engage stakeholders in the design process. Nevertheless, more studies are necessary to summarize and evaluate university research centers' spatial needs and trends, highlighting the need for further research.

In summary, benchmarking and laboratory metrics are crucial for enhancing industrial and laboratory practices. However, they present various challenges that must be addressed to ensure their effectiveness. Effective benchmarking can be achieved by establishing standardized metrics definitions, providing practical training to key personnel, and addressing permission barriers. Similarly, incorporating social and cognitive factors into laboratory metrics can promote effective knowledge sharing and collaboration within the laboratory setting, ultimately leading to improved outcomes. These efforts can help foster innovation and enhance productivity in both industrial and laboratory settings.

The present study aims to address the gap in the literature regarding the physical attributes and workspace metrics of science and research buildings from 2009 to the present. It also seeks to evaluate trends in laboratory casework to create flexible and adaptable laboratory environments. Moreover, the study aims to identify best practices for laboratory design and provide recommendations for future laboratory renovations. This information will be valuable for laboratory planners, architects, and engineers on similar science and technology projects. By thoroughly evaluating laboratory spaces, this study seeks to contribute to the knowledge base of laboratory design and improve laboratory workspaces' efficiency, functionality, and safety.

2. Methodology

2.1. Projects in the study

This research aims to analyze the evolving design metrics and benchmarks in interdisciplinary research facility design by examining the wet laboratories of three medical research facilities constructed within the last twelve years. The three projects under examination are the Indiana University School of Medicine Research Institute III (built-in 2009), the Indiana University Neurosciences Research Building (built in 2014), and the Children's Mercy Kansas City Children's Mercy Research Institute (built in 2020).

To ensure a comprehensive comparison, the study presents an overview of the three project characteristics and key features in Table 1. At the same time, Figure 1 illustrates an overview of the timelines. This research is significant as the design of research facilities plays a crucial role in shaping interdisciplinary research teams' research outcomes and productivity. Thus, it is vital to understand the priorities and paradigms in this field.

Figure 1 An overview of the project timelines (Image copyright: Author).

Table 1 Key Characteristics of the three Science and Technology buildings

Project	year	SF	Key Features
Joseph Walther Hall	2009	254,000	• 200-seat auditorium • 23,495 SF vivarium • BSL-3 research and vector production. • Cell repository • Class 10,000 clean room • DNA and serum repository • Chemistry, anatomy, gross anatomy, physiology, and toxicology laboratories
Neurosciences Research Building	2014	140,700	• Connection to outpatient neurosciences clinic • Vertical vivarium • Business incubator • Interdisciplinary teams of researchers with a disease-oriented focus • Academic medical research • Behavioral studies, neuropharmacology, electrophysiology, electrochemistry, molecular, genetics, cell biology, functional imaging, biochemistry, proteomics, computational and clinical neuroscience
Children's mercy research institute (CMRI)	2020	395,000	• Connection to outpatient, inpatient, and provider buildings • GMP facility • BSL3 research space • Mass spec space • Sequencing space • Café and 400+ person auditorium • Genomics, clinical pharmacology, immunotherapy, health outcomes, and population health

2.2. Data collection

This study utilized REVIT software for room and area measurements analysis. The data obtained from the REVIT model was exported to EXCEL and JASP software for statistical analysis. The researchers focused on specific metrics previously applied in studies examining the physical attributes of laboratory spaces that affect operational costs, technology requirements, flexibility, and collaboration outcomes.

The study evaluated three key programming metrics to inform space planning decisions. The first metric is Departmental Net Square Feet (NSF), which refers to the physical floor space available in a room or the usable floor area assigned to an open area for a given function or use. This metric is calculated from the inside wall-to-wall or the lines of the functional split. It excludes corridors, information technology (IT), mechanical, electrical, plumbing (MEP) shafts, or vertical circulation within a departmental boundary.

The second metric is Department Gross Square Footage (DGSF), which includes the sum of NSF, walls, partition thickness, and departmental corridors. It excludes shafts, IT, MEP, public or multi-departmental corridors, or public toilets. Toilets, housekeeping closets, and other support spaces given to a department are included in the DGSF. The third metric is Building Gross Square Footage (BGSF), which includes the sum of DGSF plus IT, MEP, stairs, shafts, elevators, public corridors, public toilets, lobbies, exterior wall thickness, and other non-programmed spaces. Including these additional spaces provides a comprehensive picture of the entire building area, which is essential in accurately forecasting future facility needs.

To ensure clarity and consistency in the application of programming terminologies, the study applied the following definitions for sub-departments: 1) offices, which comprises enclosed offices, workrooms, and open offices; 2) conferences, which includes conference rooms, phone rooms, or gathering rooms; and 3) the laboratory department, which includes laboratory rooms and laboratory support spaces. Due to the limited sample size, the study included different laboratory types in the research lab classification group, such as neuroscience, immunobiology, cell respiratory, open lab, genomics, or Biosafety Level 3 (BSL3). Research lab support rooms included equipment, cold rooms, lab storage, glassware wash, and gowning. In addition to departmental classifications, the study defined collaborative spaces as the combination of open-office rooms and conference spaces. Figure 2 provides an example of sub-department classification for one of the floor plans.

Figure 2 An example of sub-department classification of the Walther Hall floor plan (Image copyright: Author).

2.3. Lab Modules

Effective laboratory design is a crucial component of laboratory planning, encompassing various interior design elements, such as casework, workstations, benches, and equipment. Modular design, a vital aspect of laboratory planning, is imperative as it offers maximum flexibility, variability in space, increased efficiency opportunities, and reduced costs. The creation of a lab module, which is the minimum space required for lab occupants and equipment to function safely and effectively, involves the consideration of usable zones on both sides of an aisle, including countertops, utility cores, casework, benches, and equipment. Therefore, adopting a practical modular design approach is essential for achieving efficient lab operations.

To analyze the laboratory design in this study, the width, depth, and the number of lab modules in each lab were recorded. Additionally, the components of the lab module metrics were collected at a micro-scale level (Figure 4). These components include the linear feet, count, and square footage of lab benches and workstations, lab benches with a sink, ELNFT, which is lab space, fixed bench, loose equipment, and Biosafety Cabinets (BSC), and ELNFT/Fume Hood ratio. These metrics are essential in creating flexible and adaptable laboratory spaces that optimize efficiency, productivity, and collaboration.

Using smaller lab modules and a higher ratio of lab bench/lab workstation count can be effective strategies for creating more flexible and adaptable laboratory spaces. This approach is instrumental in creating multidisciplinary research spaces, where lab design and equipment allocation are critical in facilitating collaboration, communication, and innovation. Figure 3 provides an example of lab rooms with multiple modules as the space unit.

Figure 3 Lab modules are the unit of space for laboratory design that enable flexibility for future modifications (Image copyright: Author).

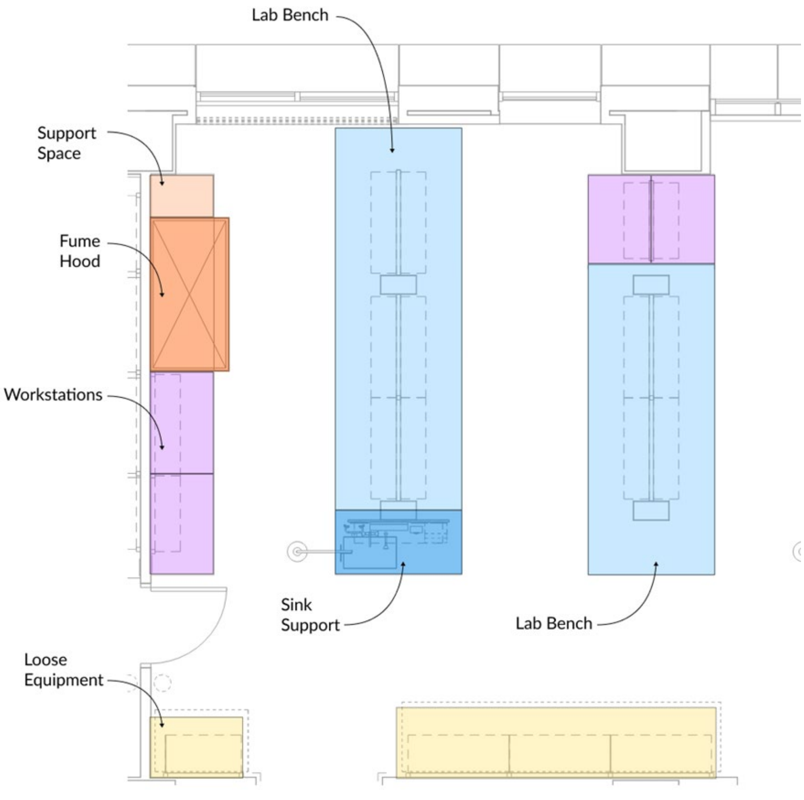


Figure 4. Components of lab modules include benches, equipment, fume hood, and lab workstations (Image copyright: Author).

2.4. Space Syntax

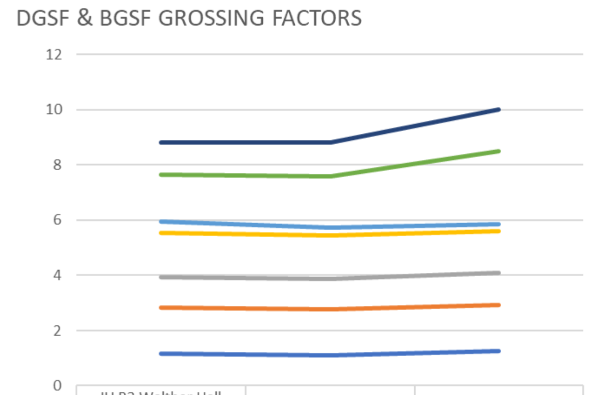
Space syntax is a sophisticated analytical methodology that utilizes mathematical algorithms to quantify spatial configuration accessibility and visibility (Hiller, 1996). Specifically, this approach generates numerical values that reflect the number of linked spaces on floor plans without changing direction, which indicates the visibility of spaces (Hiller & Hanson, 1984). Research has demonstrated that configurational accessibility is related to human behavior in research buildings, including collaboration and face-to-face communication (Hiller & Penn, 1991; Penn, et al. 1999; Toker & Gray, 2008). For instance, Penn et al. (1999) found a favorable association between employee-perceived usefulness and increased levels of spatial accessibility in research settings. They suggest higher accessibility leads to more significant work-related communication and movement opportunities, which may enhance innovation outcomes.

Recently, Zamani & Gum (2019) utilized space syntax to investigate the link between spatial attributes and staff work behaviors in an activity-based flexible office. Their results indicate that increased interaction, spatial connectivity, and seated connectivity are significantly correlated. Furthermore, departments were more likely to mix in spaces that were highly accessible and had less seated connectivity. Overall, space syntax analysis can provide valuable insights into how spatial configuration impacts human behavior and work outcomes in research buildings and can guide designers and planners in creating more effective and efficient workspaces.

3. Results

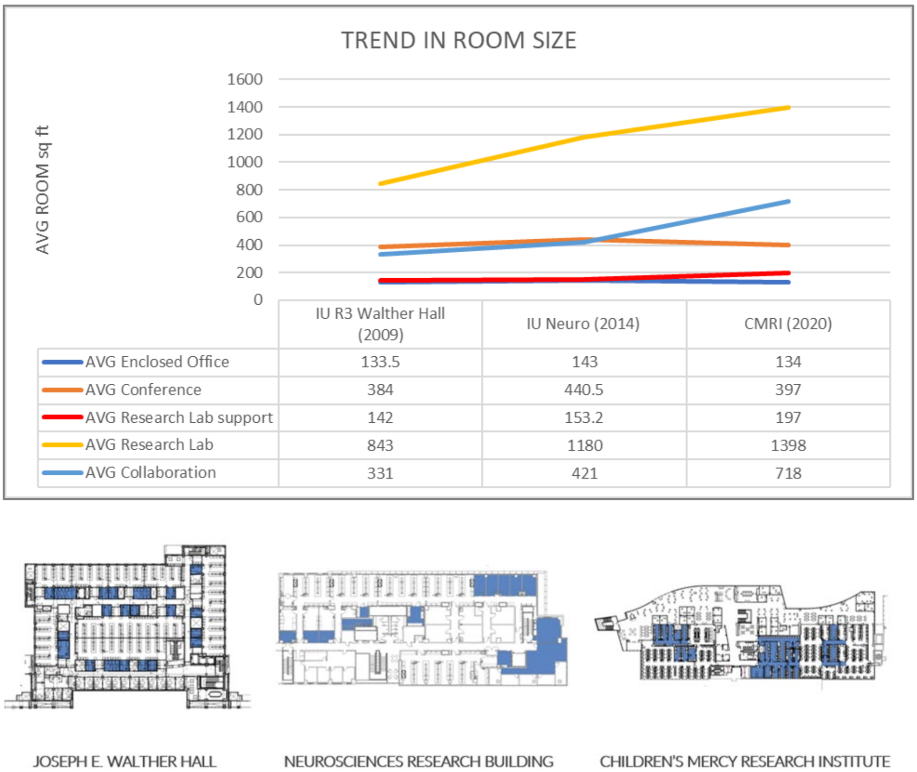
3.1. Design and Programming Trends

An ANOVA statistical analysis assessed significant mean differences across three projects. Figure 5 illustrates the trend for NSF, DGSF, and BGSF factors. The ANOVA results indicated no significant difference across the projects in terms of DGSF or BGSF grossing factors ($P > .05$). When examining the trend of key room sizes, ANOVA analysis revealed that AVG lab support and collaboration space sizes significantly increased over time ($F(2, 11) = 10.54$, $p < .05$); ($F(2, 12) = 19.965$, $p < .001$, Figure 6).



	IU R3 Walther Hall (2009)	IU Neuro (2014)	CMRI (2020)
Building DGSF factor	1.16	1.223	1.525
Building BGSF factor	1.69	1.86	2.631
Research Lab Density Ratio(NSF/floor BGSF)	0.424	0.285	0.25
Research Lab Departrment BGSF Grossing Factor	1.582	1.554	1.517
Research Lab Departrment DGSF Grossing Factor	1.109	1.114	1.151
Office Facilities Department BGSF Grossing Factor	1.684	1.663	1.68
Office Facilities Department DGSF Grossing Factor	1.15	1.099	1.262

Figure 5 Departmental NSF, DGSF, and BGSF relationships.



	IU R3 Walther Hall (2009)	IU Neuro (2014)	CMRI (2020)
AVG Enclosed Office	133.5	143	134
AVG Conference	384	440.5	397
AVG Research Lab support	142	153.2	197
AVG Research Lab	843	1180	1398
AVG Collaboration	331	421	718

Figure 6 The trend in laboratory and workplace square footage.

According to the findings presented in Figure 7, the ratios of a laboratory to lab support square footage and quantity decreased significantly over the years ($F(2, 11) = 12.087$, $p = 0.002$; $F(2, 11) = 4.893$, $p = 0.03$). The results depicted in Figure 8 compare the three projects and enclosed office spaces, indicating a significant increase in the ratio of enclosed office to lab spaces (SF).

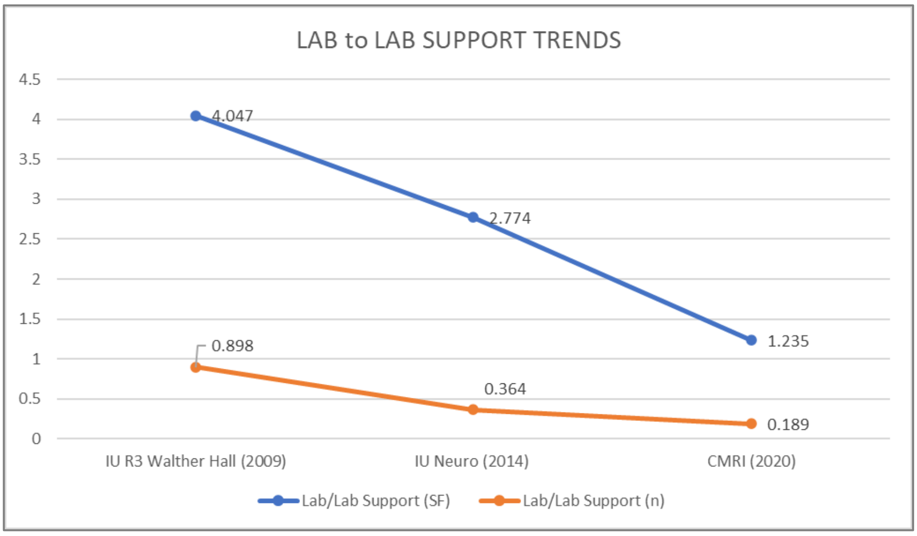
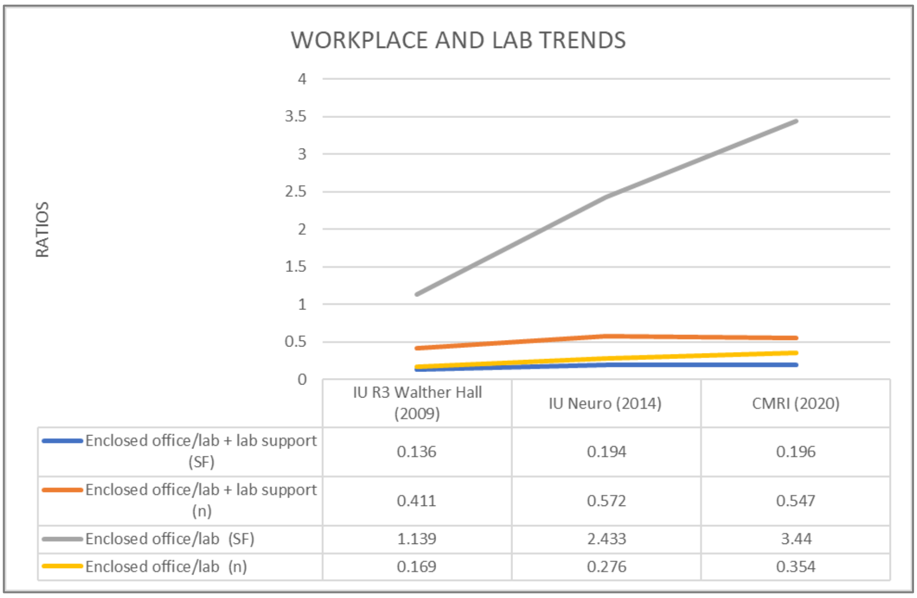


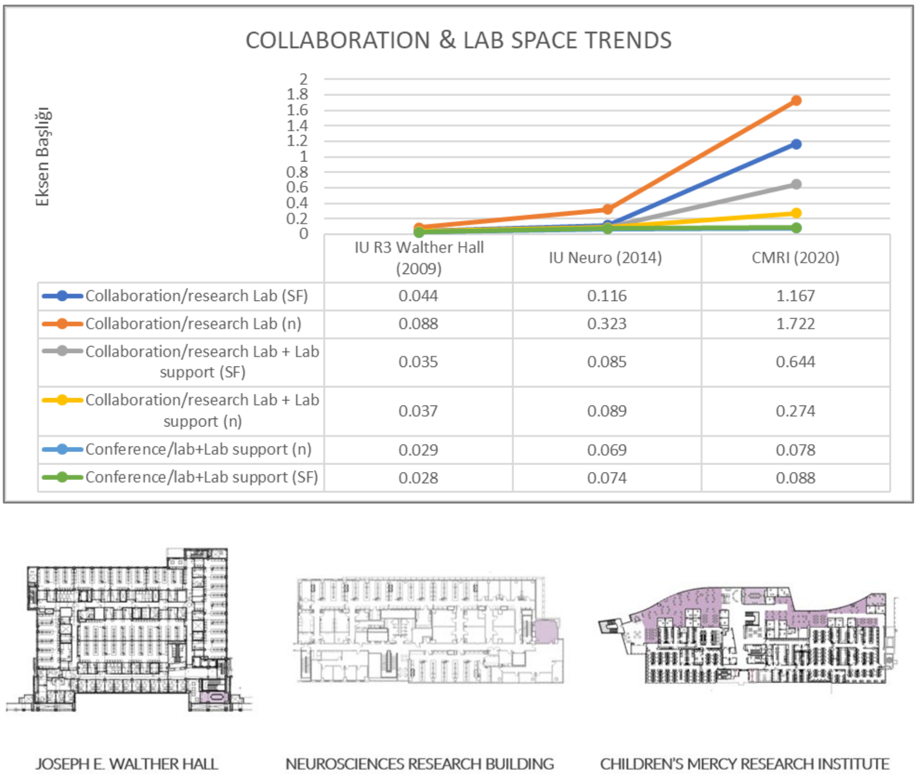
Figure 7 The ratio of lab-to-lab support decreased over time.



	IU R3 Walther Hall (2009)	IU Neuro (2014)	CMRI (2020)
Enclosed office/lab + lab support (SF)	0.136	0.194	0.196
Enclosed office/lab + lab support (n)	0.411	0.572	0.547
Enclosed office/lab (SF)	1.139	2.433	3.44
Enclosed office/lab (n)	0.169	0.276	0.354

Figure 8 Workplace and lab trends and ratios across time.

The study results revealed significant changes in the design of laboratory and workspace areas over time ($p < .001$). As Figure 9 illustrates, these changes included an increase in the ratio of collaborative spaces to lab and lab support areas and an increase in the ratio of enclosed offices to lab space. ($F(2, 11) = 6.597$, $p = 0.013$; $F(2,11) = 6.519$, $p = 0.014$, respectively).



	IU R3 Walther Hall (2009)	IU Neuro (2014)	CMRI (2020)
Collaboration/research Lab (SF)	0.044	0.116	1.167
Collaboration/research Lab (n)	0.088	0.323	1.722
Collaboration/research Lab + Lab support (SF)	0.035	0.085	0.644
Collaboration/research Lab + Lab support (n)	0.037	0.089	0.274
Conference/lab+Lab support (n)	0.029	0.069	0.078
Conference/lab+Lab support (SF)	0.028	0.074	0.088

Figure 9 Relationship between collaboration and research lab quantity and size over time.

3.2. Lab module, casework, and equipment allocations

This study compared lab modules' width and length attributes at a micro-scale level across three projects (Figure 10). Our results indicated that the width of the Walther Hall Module was significantly less than that of IU Neuro and CMRI ($F(2, 423) = 53.531$, $P < 0.001$). Furthermore, the length of the CMRI Module was significantly less than that of the older projects ($F(2, 423) = 99.243$, P <0.001). We also examined the lab module space allocation (SF) across the three projects (Figure 11) and found that the CMRI Lab module size was significantly smaller than that of both older projects ($F(2, 423) = 39.256$, $P < 0.001$). On average, Neuro Lab modules were 20 SF larger than Walther and 43 SF larger than CMRI ($P < 0.001$).

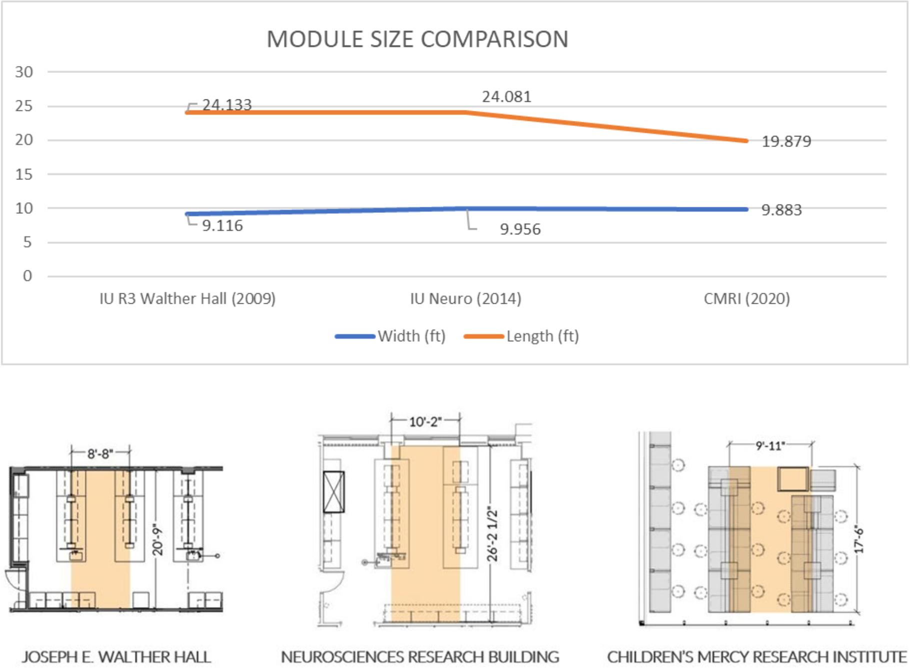


Figure 10 Lab module length and width size comparison across time.

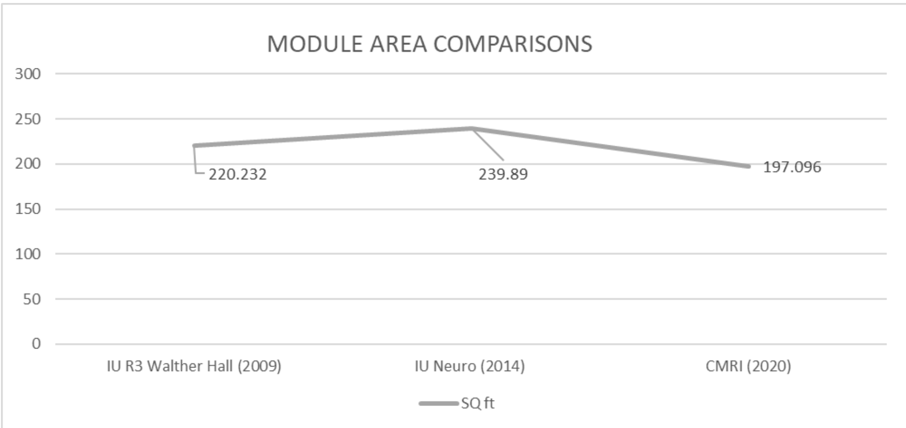


Figure 11 Average space allocation per lab module across the three projects.

The study results indicate that the ratio of lab module SF per lab room size was significantly lower in CMRI, which is attributed to smaller module sizes. This finding is supported by the statistical analysis, which shows a significant difference between the three projects ($F(2, 94) = 12.883$, $P < .001$). In addition, the CMRI project had a more significant number of lab workstations outside the lab rooms, resulting in a higher ratio of lab bench/lab workstation count. This finding is also supported by the statistical analysis, which shows a significant difference between the three projects ($F(2,88) = 15.64$, $P < .001$). However, the difference in the ratio between Walther and Neuro was insignificant ($P > .05$). Figure 12 provides a clear visual representation of the changes in lab modules across the three projects. The figure shows an increase in the count of lab modules over time, accompanied by a reduction in size.

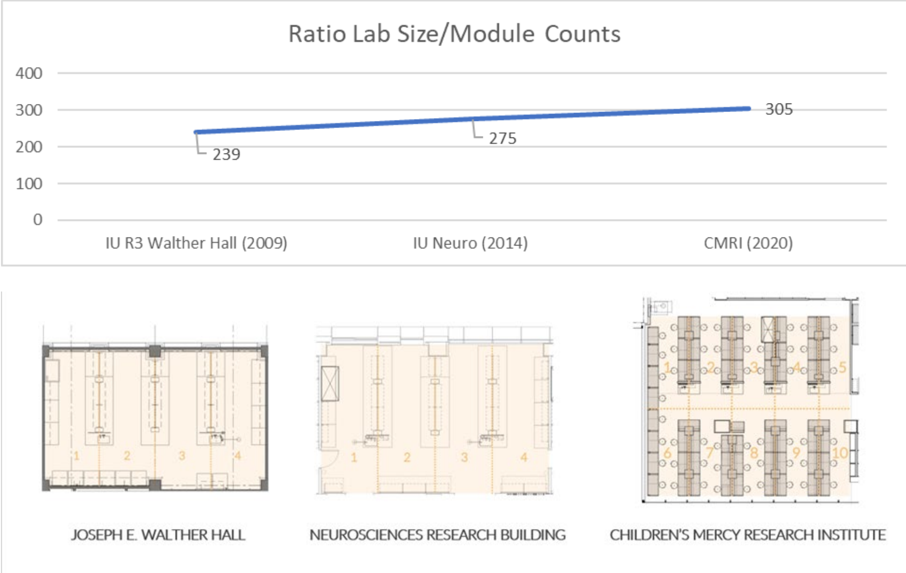
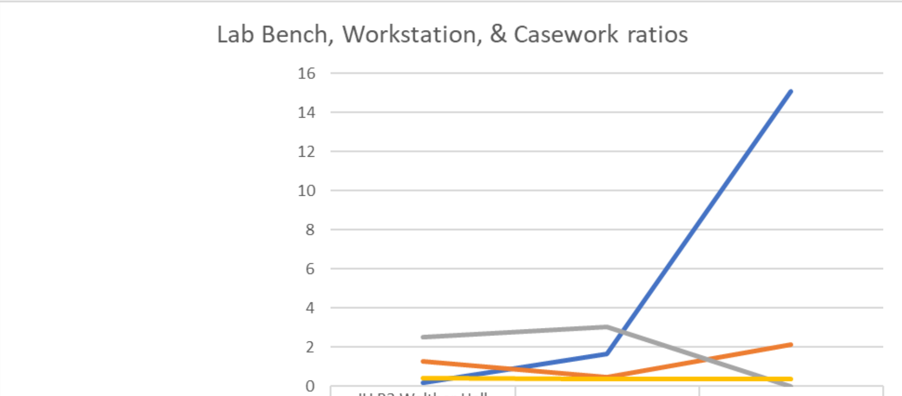


Figure 12 The average ratio of lab size to module counts per project.

The analysis presented in this study sheds light on the evolution of laboratory space and equipment allocation trends over time. Figure 13 shows that there was a significant increase in the number of sinks per lab bench, indicating a trend toward improving laboratory processes and hygiene ($F(2, 105) = 1048$, $P < .001$). Concurrently, there was a significant reduction in the allocation of casework, lab benches, fume hood, or equipment (SF) space per lab room size, resulting in increased free space for movement or work ($F(2, 108) = 12.98$, $P < .001$).

However, while these trends suggest a shift towards maximizing space utilization and reducing costs, there were no significant changes in the ratio of the Lab bench to the Lab workstation (Linear Feet) ($P > .05$). Figure 14 displays the transition of lab workstation benches across the three projects, showing a reduced number of workstation benches inside the laboratory room and their transition towards dedicated open workspace areas outside the lab room.



	IU R3 Walther Hall (2009)	IU Neuro (2014)	CMRI (2020)
lab bench/lab bench with sink	0.174	1.667	15.061
lab bench/lab workstation (count)	1.282	0.439	2.143
lab bench/lab workstation (LF)	2.52	3.04	
Casework-lab benches-fume hood-equipment (SF)/lab size (SF)	0.43	0.37	0.36

Figure 13 Lab bench, workstation, and casework trends across the projects.

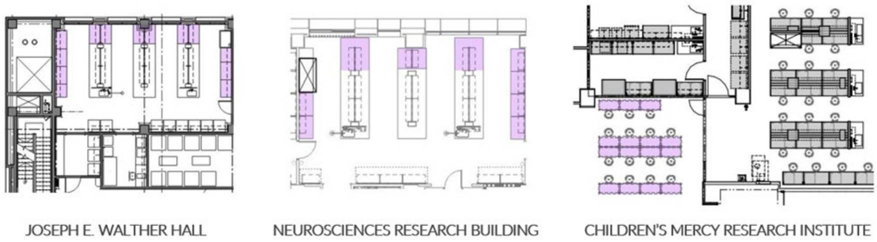


Figure 14 An example of lab workstations transitioning outside the laboratory environment within a typical floor plan.

3.3. Visibility Measures

The methodology of this study involved using the space syntax tool to measure and compare the visibility of floor plans from three different buildings. To ensure accuracy, furniture that was below eye level was excluded from the calculation. The Maximum connectivity index was used as the metric of interest, and the three buildings included in the study were Walther, Neuroscience, and CMRI. The analysis revealed that the CMRI building had the highest connectivity and visibility, with a connectivity index of 27606, compared to Walther and Neuroscience, which had 3606 and 7627, respectively. Figure 15 provides a visual representation of the connectivity values for each building, with red cells indicating highly connected areas and darker blue hues indicating lower connectivity spaces. In Walther Hall, the open lab spaces were strategically positioned at the center of the floor plan, contributing to higher visibility and connectivity within the laboratory.

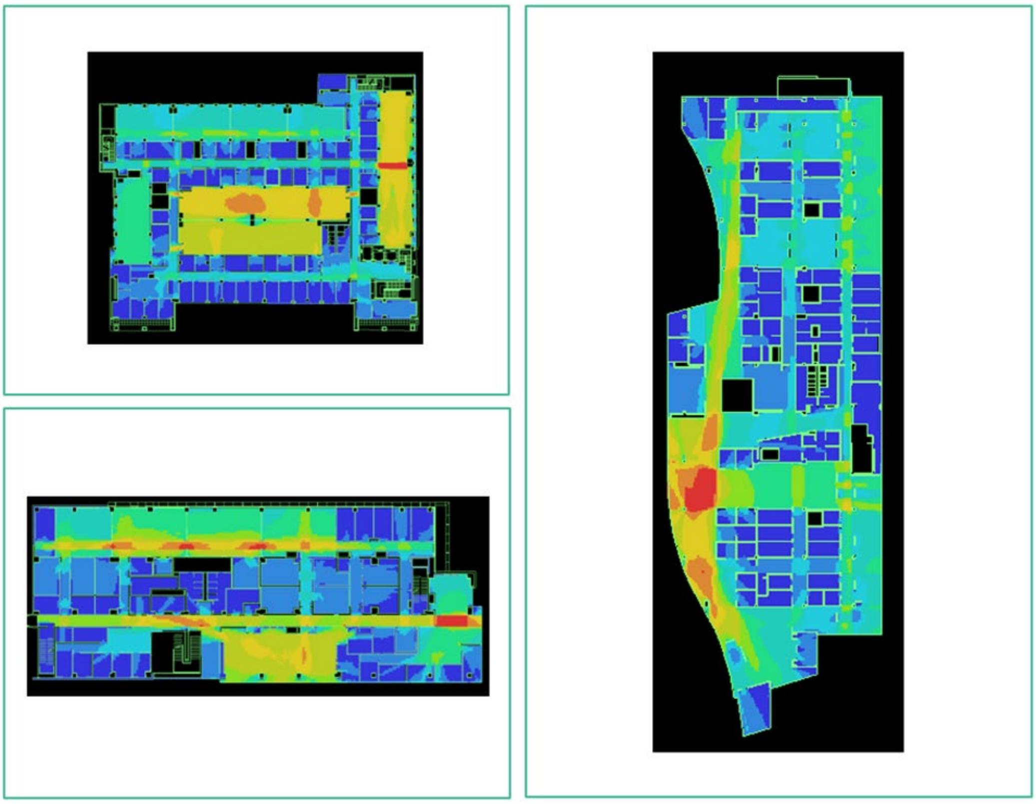


Figure 15 Visibility analysis of typical floor plans (Top left: Walther Hall, Bottom left: Neuroscience, and Right: CMRI).

The layout of the Neuro building differs from the CMRI building in terms of lab space divisions. In the Neuro building, lab spaces are divided, and the interconnecting corridors serve as the highest visibility areas. Conversely, the higher visibility areas in the CMRI building are the open workspace areas intentionally created by designers as the "heart of the building." Moreover, the contemporary laboratory layout of the CMRI building exhibits a higher connectivity index than the Walther or Neuro buildings, with connectivity indices of 3485, 2891, and 2706, respectively (Figure 16). Aside from internal connectivity, the CMRI lab rooms are positioned along exterior glass walls to enhance natural light penetration and connect users to the external environment.

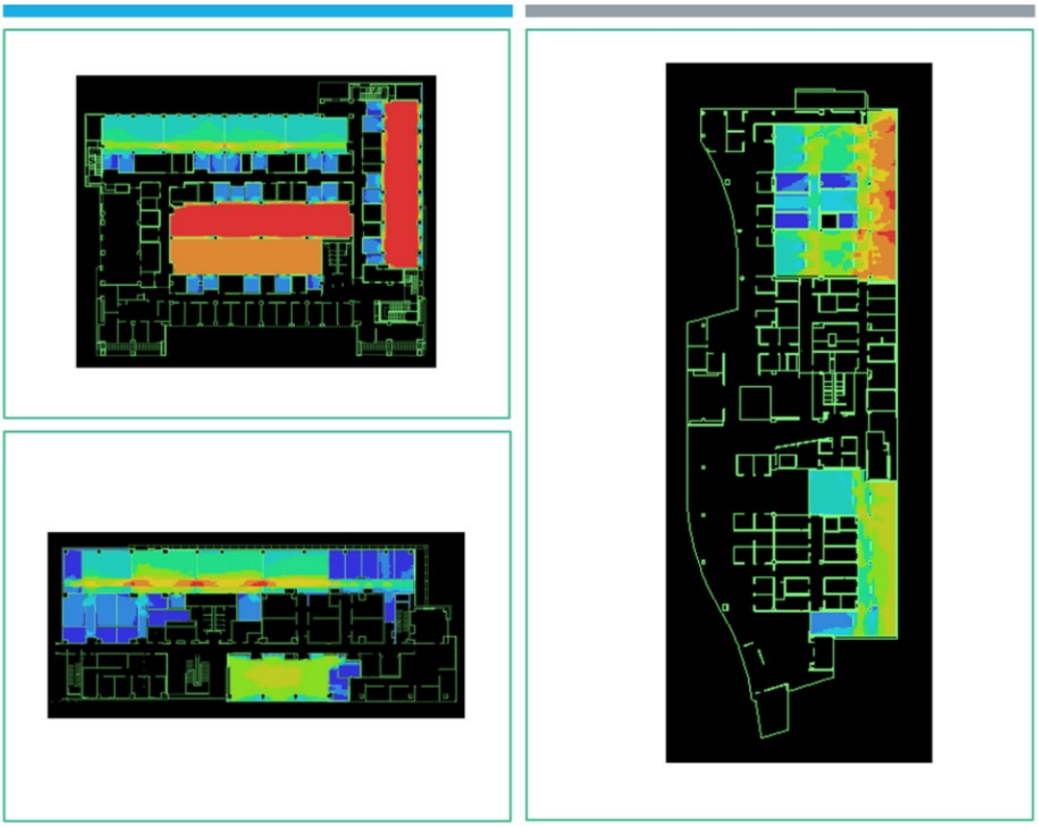


Figure 16 Visibility analysis of a typical laboratory and support room (Top left: Walther Hall, Bottom left: Neuroscience, and Right: CMRI).

4. Discussion

4.1. Design and programming implications

The design of medical research facilities has been an area of research interest for many years. Previous studies have highlighted the importance of efficient layouts, environmental controls, and flexibility in supporting interdisciplinary research team. However, with the evolution of science and technology, new priorities and paradigms have emerged that must be considered when designing interdisciplinary research facilities. The findings of this study will contribute to the existing body of knowledge in interdisciplinary research facility design by identifying the latest trends and evolving priorities in this field. Furthermore, this study can serve as a reference for future interdisciplinary research facility design research. By understanding the key features and design metrics of successful medical research facilities, researchers can develop new design guidelines for future interdisciplinary research facilities.

The study emphasizes the need to consider the evolving needs of researchers when designing research buildings. To enhance productivity, collaboration, and user experience, floor plans in laboratory spaces must be optimized. Despite a constant total area concerning NSF, DGSF, or BGSF metrics, the functionality of key rooms changed over time. As such, the study suggests a closer ratio between lab and laboratory support spaces, increased lab support numbers, and larger lab support rooms. This trend may be attributed to the growing popularity of modular lab layouts with sufficient support spaces to accommodate diverse research needs. A closer ratio of lab-to-lab support is essential as labs are becoming more generic while support areas are increasingly specialized. Thus, a closer ratio of lab and laboratory support spaces can better accommodate diverse research needs, while increasing the number and size of lab support rooms can enhance functionality.

Over the past decade, universities have increasingly emphasized a more collaborative, innovative-focused mode of operation, influencing physical environment layouts (Etzkowitz & Leydesdroff, 2000). The study found that the emergence of various office layouts, such as enclosed offices, open-plan offices, conference rooms, or co-working spaces, was a direct result of the shift in workstyles caused by the changing nature of technology, workforce, workplace collaboration, and knowledge. Findings showed that collaborative spaces are also becoming increasingly important, indicating the need to balance private work areas and collaborative spaces. These findings are consistent with previous research, indicating a growing trend toward designing collaborative, open teamwork zones and meeting spaces in research settings to promote visibility, collaboration, and innovation, enhancing employee satisfaction, comfort, and efficiency (Davis et al., 2011; Etzkowitz & Leydesdroff, 2000; Wohlers & Hertel, 2016).

The Space syntax analysis indicated that the CMRI building exhibited superior connectivity and visibility compared to the Walther and Neuroscience buildings. Notably, the layout of the CMRI building boasted a higher connectivity index, primarily attributed to the strategic placement of open workspace areas as the focal point of the building's design. The CMRI laboratory rooms were also thoughtfully positioned along exterior glass walls to optimize the natural light penetration and foster connections with the external environment. Taken together, these results suggest that the deliberate arrangement of open lab spaces and interconnecting corridors can significantly influence the connectivity and visibility of a building, particularly in the context of science and technology buildings. The implications of these findings underscore a potential shift towards a preference for highly connected open laboratories in science and technology buildings. Furthermore, the Space Syntax methodology provides a valuable tool for architects and designers to design well-connected and visible spaces in science and technology buildings during pre-construction.

This space syntax finding aligns with the trend towards open office layouts with a higher need for visibility and accessibility, which enhances the likelihood of unplanned consultations among coworkers (Toker & Gray 2008). This is particularly important for scientists who depend on face-to-face communication for collaboration and information exchange (Toker & Gray, 2008). However, research has also shown that open office spaces can result in overcrowding, noise, and distractions, reducing productivity and job satisfaction while increasing employee stress levels (Davis et al., 2011; Elsbach & Bechky, 2007). To address these issues, office designers have turned to multi-space environments, such as activity-based flexible offices or combi offices, which provide a range of workspaces to meet diverse work requirements (Zamani & Gum, 2019).

Our research findings indicate an increasing proportion of enclosed offices compared to laboratory spaces. This trend may signify a need for a more balanced distribution of open and private enclosed spaces, particularly for dry lab and computational tasks, as highlighted in previous studies (Wohlers & Hertel, 2016; Heinzen, et al., 2018). For instance, Watch's (2001) observational study found that laboratory users tend to spend half of their time in private offices. Private offices offer individualized research environments, greater privacy, and lower noise levels, essential for focused tasks (Lee, 2010; Wajcman & Rose, 2011). In addition to providing a quiet and private environment, enclosed offices offer several other advantages, including increased personalization, autonomy, and control over one's workspace (Sundstrom et al., 1986).

Furthermore, research has shown that the availability of private offices is positively associated with employee job satisfaction and well-being (Kim & De Dear 2013; Raziq & Maulabakhsh, 2015; Zamani & Gum 2019). However, the implementation of enclosed office spaces must be balanced with the need for collaboration and interaction among laboratory users. Thus, it is vital to strike a balance between the availability of private and open spaces in laboratory environments to enhance overall productivity and employee satisfaction. Future studies could explore the most effective distribution of open and private enclosed spaces in laboratory environments, considering the factors influencing employee productivity and well-being. Additionally, the research could examine the impact of different office configurations on employee satisfaction and well-being, using qualitative and quantitative methods to collect data on employee experiences and preferences. Overall, our research highlights the growing importance of private enclosed spaces in laboratory environments and suggests a more balanced distribution of open and private spaces to enhance productivity and employee satisfaction.

The COVID-19 pandemic changed employee expectations for workspaces, with a growing demand for a combination of collaborative and comfortable home-like features (Kniffin et al., 2021). This shift has led to workspaces incorporating living room setups with plush couches, flexible furniture for breakout groups, and hideaway pods for employee privacy and autonomy.

Moreover, the increase in remote work has reduced the future demand for office and computational workspace. At the same time, meeting rooms, huddle areas, and amenity spaces may rise in importance to encourage collaboration during office visits. Another trend is to move write-up desks into workplace areas, adopting hot-desking and hoteling workstation models to promote collaboration and increase spatial efficiency. Nevertheless, implementing these changes in the post-pandemic era requires an objective evaluation of workspace needs to make informed planning decisions (Kniffin et al., 2021). Such assessments should consider the factors contributing to employee productivity and satisfaction, including noise levels, lighting, and ergonomic furniture. Additionally, an analysis of the benefits and drawbacks of remote work should be considered, along with the potential impact on employee communication and team collaboration.

In designing laboratory workspaces that promote productivity and well-being, studies that employ qualitative and quantitative methods to gather data on employee preferences and behaviors and objective measures of productivity and job satisfaction can be particularly useful. For example, studies on laboratory users' productivity and well-being can determine the optimal balance of open and enclosed spaces to foster productivity and collaboration. Furthermore, research on environmental factors such as lighting, temperature, and air quality can offer insights into designing workspaces conducive to employee performance and health. For instance, investigations into the impact of natural lighting and indoor plants on employees' moods and productivity could be informative. In conclusion, incorporating home-like features, providing focused and collaborative workspaces, and promoting spatial efficiency can be advantageous for S&T organizations to adapt to the changing needs of employees. To improve laboratory workspace design, future research should continue to explore the most influential workspace configurations and the impact of environmental factors on laboratory users' productivity and well-being.

4.2. Lab module, casework, and equipment

In laboratory spaces, satisfaction with safety and security is a critical metric (Mahmoud, et al., 2018). The appropriate size of lab modules is essential for managing initial and long-term operational and construction costs. Modules with wider widths can dedicate casework, bench, or casework area to unnecessary circulation areas, while narrow modules can create unsafe research environments. Consistent with our findings, recent reports indicate a trend towards smaller lab modules to enhance productivity and collaboration between the principal investigator (PI) and research team members (Skolozdra, 2012).

The metrics also reveal an increasing trend in using lab benches with sinks. This trend was influenced by lab users requesting reduced steps and improved accessibility to sinks in the laboratory environment. However, there is a need for more empirical studies to determine whether this relationship between improved productivity and efficiency is significant. Future research could focus on collecting data from laboratory users regarding their experiences with varying sizes and configurations of lab modules. Researchers could also collect objective measures of productivity and efficiency to determine whether the use of smaller lab modules and lab benches with sinks positively impacts laboratory performance.

Overall, these findings suggest that laboratory designers and managers should carefully consider the size and configuration of lab modules and the inclusion of lab benches with sinks to optimize productivity and efficiency in laboratory environments. The present study's findings indicate a decrease in the ratio of laboratory workstations to lab benches. This trend can be attributed to the increasing use of computers and digital workstations, which has resulted in laboratory benches being used as writing surfaces, thereby altering the traditional requirement for workstation benches. Researchers have observed a shift in the location of conversations from lab benches to desks and open multi-office areas to reduce disruption and noise for colleagues (Coradi, et al., 2015; Heinzen et al., 2018). Furthermore, relocating workstation benches to areas outside the laboratory can provide a safer workspace for storing food, books, and paper. However, empirical research is needed to determine whether transitioning workplace benches to outside lab rooms improves cost, satisfaction, and productivity.

Limited studies have specifically examined the effects of relocating laboratory workstations on cost, satisfaction, and productivity. Future research in this area may consider conducting surveys and interviews with laboratory personnel to assess their satisfaction with the new workstation arrangement and to identify any potential cost savings resulting from the relocation of workstations. In addition, objective measures such as productivity and efficiency data could be collected to determine whether the new arrangement has a positive or negative impact on laboratory performance.

5. Conclusion

In conclusion, this study comprehensively analyzes the wet laboratories of three medical research facilities constructed within the last twelve years. By examining these facilities' design metrics and benchmarks, the study highlights the new priorities and paradigms in interdisciplinary research facility design. The results of this study will be valuable for researchers, laboratory planners, architects, and engineers involved in the design of interdisciplinary research facilities. The study's findings suggest that optimizing lab space allocation and workstation placement can maximize efficiency and productivity in the laboratory. The study highlights the importance of optimizing floor plans in laboratory spaces to enhance productivity, collaboration, and user experience. The trend towards designing collaborative, open teamwork zones and meeting spaces in research settings align with previous research, indicating a growing need for visibility and accessibility. The increasing proportion of enclosed offices compared to laboratory spaces indicates a need for a more balanced distribution of open and private enclosed spaces to meet diverse work requirements, particularly for dry lab and computational tasks. Enclosed offices offer several advantages, including increased personalization, autonomy, and control over one's workspace. The collective results of the space syntax analysis indicated that a purposeful organization of open laboratory spaces and interconnecting corridors profoundly impacts the connectivity and visibility of a building, particularly in the domain of science and technology buildings. These findings suggest a potential trend toward a preference for highly connected open laboratories in such settings.

The research findings suggest a trend towards smaller lab modules and using lab benches with sinks to improve productivity and collaboration. However, there is a need for more empirical studies to validate this relationship. Furthermore, the study observes a shift in the location of conversations from lab benches to desks and open multi-office areas and recommends the relocation of workstation benches outside the laboratory to provide a safer workspace for storing food, books, and paper. Finally, the study calls for further research to explore the impact of relocating laboratory workstations on cost, satisfaction, and productivity.

Further research is necessary to investigate the impact of design trends on laboratory and office spaces, ensuring that they are optimized for productivity, cost-effectiveness, and employee satisfaction. Longitudinal studies involving stakeholders are necessary to ensure construct validity and generalizability of the results. Correlations between laboratory design, workspace attributes, and implied outcomes should also be explored to determine whether open lab layouts are associated with higher productivity, collaboration, or communication outcomes. Engaging laboratory users in these studies would be interesting. Lastly, the inconsistent data entry and terminologies across projects resulted in a lengthy process of standardizing architectural metrics. To facilitate database development and continuous updates across time, we recommend creating a standard room naming protocol with associated descriptions for architectural companies.

Acknowledgment

The Author thanks the following individuals for their assistance during the benchmarking phase of this manuscript: Kiatlyn Gardner, Jason Kachanovsky, Kristen Rickord, Lauren Silvers, Staci Alatsis.

References

Ancona, D.G. (1990). Outward bound: strategies for team survival in an organization. *Academy of Management Journal, 33*(2), 334–365.

Ancona, D.G., & Caldwell, D.F. (1992). Bridging the boundary: External activity and performance in organizational teams. *Administrative Science Quarterly, 37*(4), 634–665.

Coradi, A., Heinzen, M., & Boutellier, R. (2015). A longitudinal study of workspace design for knowledge exploration and exploitation in the research and development process. *Creativity and Innovation Management, 24*(1), 55-71.

Davis, M. C., Leach, D. J. & Clegg, C. W. (2011 a). *The physical environment of the office: Contemporary and emerging issues*. In: Hodgkinson, G. P. Ford, J. K, eds. International Review of Industrial and Organizational Psychology. Chichester, UK: Wiley, pp. 193 – 235.

Elsbach, K. D. & Bechky, B. A. (2007). It's more than a desk: Working smarter through leveraged office design. *California Management Review, 49*(2), 80-101.

Etzkowitz, H., & Leydesdorff, H. (2000). The future of the university and the university of the future: evolution of ivory tower to entrepreneurial paradigm. *Research Policy, 29*(2), 313–330.

Heinzen, M., Cacciatori, E., Zoller, F. A., & Boutellier, R. (2018). Who talks to whom about what? How interdisciplinary communication and knowledge of expertise distribution improve in integrated RandD labs. *Ergonomics, 61*(8), 1139-1153.

Hillier, B. & Penn, A. (1991). Visible Colleges: Structure and Randomness in the Place of Discovery. *Science in Context, 4*(1), 23 – 49.

Hillier, B. (1996). *Space is the Machine: A Configurational Theory of Architecture*. Cambridge University Press, Cambridge.

Hillier, B., & Hanson, J. (1984). *The Social Logic of Space*. Cambridge University Press, Cambridge.

Kahn, B. K., Strong, D. M., & Wang, R. Y. (2002). Information quality benchmarks: product and service performance. *Communications of the ACM, 45*(4), 184–192.

Kelly, D., & Pingel, M. J. (2022). Space use and the physical attributes of acute care units: A quantitative study. HERD: Health Environments *Research and Design Journal, 15*(1), 222–238.

Kim, J., & De Dear, R. (2013). Workspace satisfaction: The privacy-communication trade-off in open-plan offices. Journal of Environmental Psychology, 36, 18-26.

Kniffin, K. M., Narayanan, J., Anseel, F., Antonakis, J., Ashford, S. P., Bakker, A. B., ... & Vugt, M. V. (2021). COVID-19 and the workplace: Implications, issues, and insights for future research and action. *American psychologist, 76*(1), 63.

Lee, Y. S. (2010). Office layout affecting privacy, interaction, and acoustic quality in LEED-certified buildings. *Building and Environment, 45*(7), 1594–1600.

Mahmoud, A. S., Sanni-Anibire, M. O., Hassanain, M. A., & Ahmed, W. (2018). Key performance indicators for the evaluation of academic and research laboratory facilities. International Journal of Building Pathology and Adaptation, 37(2), pp. 208-230. https://doi.org/10.1108/IJBPA-08-2018-0066

Penn, A., Desyllas, J., & Vaughan, L. (1999). The space of innovation: interaction and communication in the work environment. *Environment and planning B: Planning and design, 26*(2), 193-218.

Raziq, A., & Maulabakhsh, R. (2015). Impact of working environment on job satisfaction. Procedia Economics and Finance, 23, 717-725.

Skolozdra, R. (2012). How Smart Lab Design and Layout Ensure Optimal Procedures, Workflow, Cooperation, and Productivity. Lab Manager. Access April 2022 from: https://www.labmanager.com/lab-design-and-furnishings/it-s-all-in-the-planning-how-smart-lab-design-and-layout-ensure-optimal-procedures-workflow-cooperation-and-productivity-15697 .

Sundstrom, E., Burt, R., & Kamp, D. (1986). Privacy at work: Architectural correlates of job satisfaction and job performance. *Academy of Management Journal, 29*(2), 404-417.

Toker, U., & Gray, D. O. (2008). Innovation spaces: Workspace planning and innovation in US university research centers. *Research Policy, 37*(2), 309–329.

Watch, D., 2001*. Building Type Basics for Research Laboratories*. John Wiley & Sons, New York.

Wajcman, J. & Rose, E. (2011). Constant connectivity: Rethinking interruptions at work. *Organization Studies, 32*(7), 941-961.

Wohlers, C., & Hertel, G. (2016). Choosing where to work at work–towards a theoretical model of benefits and risks of activity-based flexible offices. *Ergonomics, 60*(4), 467-486.

Zamani, Z., & Gum, D. (2019). Activity-based flexible office: Exploring the fit between physical environment qualities and user needs impacting satisfaction, communication, collaboration, and productivity. *Journal of Corporate Real Estate, 21*(3), 234-253.

Resume

Zahra is the director of research at BSA LifeStructures and leads various projects such as simulation modeling, Post-Occupancy Evaluations (POE), and benchmarking reports. She is passionate about studying the impact of design and planning decisions on human experience, satisfaction, health, and well-being. Zahra's expertise in data management, analysis, integration, environmental psychology, public engagement, team collaboration, problem-solving, creativity, and publication makes her a valuable team member. She is interested in exploring human dimensions and social needs in connection with design. Zahra has published and presented her research in multiple journals and international conferences. Her contributions to the industry include market research, customer needs analysis, and providing innovative solutions to complex problems.