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Review

A Review of Physical and Digital Mock-Up Applications in Healthcare Building Development

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Abstract: Mock-up simulation is a design or human factor research method to help designers identify key design issues and factors of a product or environment. This paper discusses physical mock-up (PMU) and digital mock-up (DMU) applications in healthcare building development through a narrative literature review. The following questions are addressed in this paper: what would the purposes of using PMU or DMU simulations be? At which phase of a hospital design would a PMU or DMU simulation be used? What methods can be used to conduct PMU and DMU simulations? The paper discusses the advantages and disadvantages of these two mock-up methods and highlights the importance of clinical staff's involvement in mock-up simulations. It gives recommendations for the design practitioners or project managers of healthcare building development recommendations to implement these two mock-up methods in healthcare building development projects.

Keywords: healthcare building design; physical mock-up; digital mock-up; evidence-based design; virtual reality

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1. Introduction

Mock-up simulation is one design or human factor research method that plays an essential role in products and physical environment design. There are two major types of mock-ups, namely, physical and digital. A physical mock-up (PMU) is a full-scale model or replica, while a digital mock-up (DMU) is a collection of 3D models made before the real-life version is built. Both mock-up methods represent the form of a machine, a structure, or a design to be developed, built, or improved. They are also used to study and demonstrate potential solutions [1,2]. Mock-ups can be used to support concept development and design decision-making by examining or testing the simulated or planned settings and proposed activities. They can also evaluate or test individual preferences, behavior patterns, and health and safety issues exposed to alternative environmental arrangements [3–13]. In terms of demonstration, mock-ups are frequently applied to preview and visualize products or complex settings prior to the design and production; and train students and professionals [14–16]. There has been a wide range of simulations based on these two types of mock-ups used in the aeronautical, automotive, and retail industries with a large degree of success [17,18].

In architectural design, architects sometimes evolve their design work without considering the complex human responses to the built environment. In his book "*The Nature of Order: A Vision of a Living World*," Alexander pointed out that a fundamental problem in the design process is that architects often ignore the users' feelings, experiences, and reactions in the spaces. He suggested the design must be done in a situation similar to the actual situation, in which spaces can be adapted to the users and their work [19].

The planning and design of healthcare systems and facilities are often complex processes, as they need to provide settings for a wide range of clinicians' activities and accommodate patients with increasing expectations regarding the quality of service provided [1,4]. If stakeholder engagement is effectively used, it can ensure that a wide range of current and future users' needs are taken into account [1,4–8]. Clinical staff are a valuable and reliable source of information about patients' care and treatment and the functional requirements of their workplace. Alexander suggested that the size of a space or a room is critically vital and can affect its usefulness beyond what the architects imagine [19]. In the healthcare setting, 0.5 m short in the length or width of a clinical room could affect the safety and efficiency of care and treatment and even lead to a dysfunctional room. As experienced users of healthcare systems and facilities, the clinical staff can provide valuable input into the planning and design process [18]. However, how can the clinical staff effectively communicate with architects about the functional requirements of a specific clinical area; and how would they be able to effectively monitor the architectural process to assure that those requirements will be met in a designed area? It is recommended that conducting mock-up simulations can help clinical staff understand the design language and help architects understand the clinical practice and medical technology [17,18,20,21]. The language of clinical staff and a design team will thus be brought together, and a bridge can be built to cover the knowledge gap between them.

Depending on the problems to be addressed and the client's budget or requirements, a PMU simulation can range between a very basic level and a highly complex level (Figure 1). Sometimes a full-size mock-up could be simple and cheap with the equipment and furniture made from lightweight materials such as cardboard [18,21–23]. The walls of a simulated room or space can also be represented with lightweight materials, e.g., wood and cardboard. Most design issues can be addressed by performing relevant task scenarios in inexpensive mock-ups. A fully furnished and equipped mock-up represents the actual design for demonstration and display. It is usually built as a record of the final solutions agreed by all parties. However, for the purpose of design or evaluation, expensive mock-ups are not necessary, as long as the layout and dimensions of a mock-up closely represent the actual design being tested or evaluated.

Figure 1. A simple PMU and a fully furnished and equipped PMU.

In manufacturing and many other industries, there is an increasing demand to decrease development costs of new products and produce solutions faster than ever. At the same time, products are becoming more complex, and stakeholders/end-users play an increasing role within the design process. This has led to increased applications of IT and DMU technologies (e.g., CAD, BIM, virtual reality) in the product development process. A DMU can be considered a collection of 3D models representing the form of a product or environment to be developed or tested before the physical system or solution is built. It allows stakeholders to experience the modelled rooms or spaces via computer screens or VR goggles.

Some international case studies indicate that mock-up simulations have become essential for evidence-based design (EBD) solutions in healthcare development [1,4–14,18,20]. However, the initial literature search suggests that there is little information on the applications of mock-ups in the design of healthcare systems and facilities in China. This paper reviews the literature on PMU and DMU simulations from an international perspective in the field. It attempts to identify credible evidence and practical applications to give the design practitioners or project managers some recommendations to implement these two mock-up methods, which can support the EBD of healthcare facilities in China.

2. Method

There are three main research approaches in academic disciplines: positivism, post-positivism, and interpretivism [24–27]. Positivism is purely objective and concerned with explaining and testing theories. Interpretivism aims to understand the complexities that are being studied [24,25,27]. Post-positivism bridges the gap between positivism and interpretivism. It explains and understands the phenomena in the studies [24,25]. The epistemological position of this paper is interpretivism, as it is concerned with understanding the applications of PMU and DMU simulations. A narrative literature review was chosen to help researchers discover and review the available literature to provide a broad overview of a topic within a body of knowledge or identify possible gaps and draw conclusions in the literature [28–31]. The authors standardized the review process to increase the objectivity and addressed the following questions.

- What would the purposes of using PMU or DMU simulations be?
- At which phase of a hospital design would a PMU or DMU simulation be used, and what outcomes can be achieved?
- What methods can be used to conduct PMU and DMU simulations?

The literature search covered online and offline resources to identify and retrieve archival documents on the applications of mock-up simulations for healthcare design and development. The general and specific Internet resources included PubMed, ProQuest, Science Direct, Scopus, and China National Knowledge Infrastructure (CNKI). An extensive search of Google, Google Scholar, and websites of Healthcare Design (HCD) Magazine and the AIA Academy Journal of the Academy of Architecture for Healthcare (AAH) was conducted to identify a broader range of literature.

The search focused on the purposes and the timing of using mock-up simulations; and the process of achieving the purposes, with a combination of keywords listed in Table 1. The snowballing method was also used to search for additional literature, during which a Sage journal, Health Environments Research & Design (HERD), was identified, as it was found that the majority of empirical studies in the field were disseminated in it. A manual search was then conducted for this journal.

Table 1. Keywords used in literature searches.

Term of Mock-Up Simulation	Simulated Environment	Purpose/Intervention
Mock-up	Hospital	Design/development
Physical mock-up	Healthcare facility	Assessment
Digital mock-up	Health facility	Evaluation
Prototype	Medical Centre	Improvement
Prototyping mock-up/model	Medical facility	Improvement
Physical/real-time prototype	Healthcare infrastructure	Functionality/function
Physical/real-time prototyping mock-up	Hospital department	Layout
Digital/virtual prototype	Hospital room	Clinical activity
Digital/virtual prototyping mock-up	Medical space	Efficiency
Simulation		Flexibility/adaptability
Modelling		Patient safety
Virtual reality		Cost
		Model of care
		User
		Participation
		Human factors

The following search criteria were used to include publications and to ensure that the search results are relevant: (1) studies on healthcare assets; (2) being published from 2000 to the present; and (3) providing empirical evidence (e.g., data, findings).

3. Results

The literature search result showed that most publications were project reports, technical reports, conference papers, blogs, working papers, newsletters, and presentations, providing general descriptions or brief discussions on the mock-up applications. Eventually 16 references were extracted from 114 relevant publications which had been reviewed (Table 2). Some gray literature disseminated by non-academic publishing channels, such as HCD Magazine, AIA KnowledgeNet, and some hospital websites, was retrieved to support the discussion.

Table 2. Summary of empirical studies of applying mock-ups to healthcare design and development.

Type of Mock-Ups	Authors	Purposes/Issues Addressed	Phases	Data Collection Methods	Outcomes/Achievements
PMU	Hignett, Lu, and Fray [4]	A cardiac intensive care unit and a neonatal intensive care, to determine functional space requirements for key clinical activities	Conceptual design, or design evaluation	Observation, video recording	The average functional space was identified. The findings were incorporated into government guidance.
PMU	Durham and Kenyon [5]	A low-acuity emergency department cubicle, to explore the design concept	Conceptual design	Feedback	A cubical size for a single patient and the options for converting the cubicles to multiple patient spaces were recommended. A preliminary departmental layout and equipment were also recommended.
PMU	Durham and Kenyon [5]	Medical–surgical and ICU rooms, to improve the designs by engaging users in the design process	Schematic design, or design development	Feedback	The locations of the wall-mounted computers and other wall-mounted items were adjusted based on the users' feedback and the design team's review.
PMU	Durham and Kenyon [5]	A medical–surgical room and an ICU room, to allow user reviews and final sing-off on space designs	Construction documents	Feedback	The location of selected light switches and the finishes in the rooms were slightly changed.
PMU	Sachs et al. [6]	A patient room and bathroom, to evaluate the design proposal	Design evaluation	Feedback forms (questionnaire) and listening sessions (focus group)	Detailed design of room layouts, furniture, daylight, materials etc., was evaluated qualitatively and quantitatively. A PMU was concluded to be an effective tool for design and evaluation applications.
PMU	Evans et al. [7]	Prototype rooms for portable bedside imaging	Conceptual design, design evaluation	Interview and focus group session	Results suggested that a working area surrounding the patient's bed for imaging is important. The designs should consider the imaging professionals providing the diagnostic patient care at the bedside and reduce the work-related musculoskeletal disorder risks.
PMU	Shultz et al. [8]	A universal operating room, to evaluate its layout	Conceptual design, design development and construction documents	Video recording (observation) and feedback (questionnaire)	Doors, booms, equipment, and supplies of the room template were relocated. The workstations were reconfigured. The recommendations were retested for the development and evaluation of the future design. It concluded that incorporating the recommended design changes resulted in better room functionality.
PMU	Pati et al. [9]	A patient room and bathroom, to look at the relationship of the role of the physical environment and patient falls	Conceptual design, or design evaluation	Video recording of the observed postures and in-depth query and expert critique	Five physical design elements of the room associated with clinicians' postures were identified. Patient falls could be reduced through appropriate tests and reviews of the design elements.
PMU	Graves et al. [12]	A patient room, to explore and evaluate nurses' perceptions of different lighting conditions in it.	Conceptual design, or design evaluation	Interview, a set of rating scales to measure the lighting conditions	Results provided nurses' perceptions of the lighting distribution, favorable lighting zones, the use of colored lighting, and lighting at night. It would help architects understand the potential benefits and concerns of new features for lighting systems.

Table 2. *Cont.*

Type of Mock-Ups	Authors	Purposes/Issues Addressed	Phases	Data Collection Methods	Outcomes/Achievements
PMU	DuBose et al. [13]	A patient room, to explore how aspects of lighting were experienced and evaluated by patients	Conceptual design, or design evaluation	Questionnaire	Results provided patients' perceptions of the lighting distribution, favorable lighting zones, the use of luminaire CCTs and colored lighting.
PMU	Watkins, Myers, and Villasante [17]	Patient rooms including acute care, ICU and isolation rooms, to test and establish EBD standards	Conceptual design, or design evaluation	Questionnaire and observation	Results identified space requirements, optimum clearances for operations, optimum room configurations, room size, room volume, the functional arrangement of furnishings, etc. Results also provided EBD guidelines.
PMU	Peavey, Zoss, and Watkins [32]	Three-phase PMUs for a medical-surgical patient room, to test the design assumptions	Conceptual design	Focus group, questionnaire, observation	Operational and design concepts, user safety, caregiver satisfaction, equipment usage, space utilization, and users' experience were evaluated.
PMU	Traversari, Goedhart, and Schraagen [33]	An operating room, to evaluate the design for the optimization of the layout for workflows	Design development	Video recording (observation)	Results identified space requirements, optimum clearances for operations, optimum room configurations, room size, and equipment arrangement.
PMU	Bayramzadeh et al. [34]	An operating room, to develop a toolkit for design and evaluation of operating room prototypes	Conceptual design, design development	Observation and focus group	The paper described the PMU process in detail. An evaluation toolkit wad developed to help stakeholders decide the room size and zoning, the location of OR tables and doors, and visualize the workspace to provide feedback.
PMU	Colman et al. [35]	A set of full-scale cardboard mock-ups to evaluate the design of 11 clinical areas	Schematic design	Simulation-based hospital design testing (SbHDT) method, i.e., simulation scenarios, debriefing and failure mode and effect analysis (FMEA) scoring	The SbHDT method was described in detail to statistically identify and effectively mitigate safety concerns during the facility design. It demonstrated a collaborative process where clinical staff, architects and facilitators of PMU simulations better understood each other's point of view.
DMU	Dunston, Arns, and McGlothlin [36]	A DMU for an existing patient room in the Bariatrics and Obstetrics department, to review critical design aspects	Design development	Feedback	The DMU reviewed detailed design aspects such as mobility of equipment; dimensions and placement of doors, windows and cabinetry; accessibility and safety of the bathrooms etc., helped stakeholders identify potential issues early in the project process and recognize the existing issues in the actual patient room. A HUB for the design of virtual healthcare environments would be developed.
DMU	Peavey, Zoss, and Watkins [32]	A DMU for an operating room, to gain user perspectives about efficiency and safety of the proposed design	Design development	Focus group, questionnaire	Results informed some of the design modifications and solutions to vacuum and telecom outlets (for operational flexibility), two universal booms, a fixed work station (for optimal visibility).
Both	Durham and Kenyon [5]	Rough PMUs of key rooms to review the design; the DMU of an operating room to allow users to stand in the PMU, and helped them fully understand the space and give their feedback.	Conceptual design, schematic design and design development	Feedback	The PMUs validated the proposed size and shape of the rooms and provided suggestions for improving the room functionality. The DMU helped users confirm the room size, shape and provide feedback on some key issues such as where to locate the booms, major equipment, and the nurse's workstation.
Both	Durham and Kenyon [5]	Rough PMUs and DMUs of the multiuse care room and infusion bays, to develop new room types, to test whether the new concept would meet the patient's needs and be more functional.	Conceptual design	Feedback (handwritten notes taped to the walls)	PMU results confirmed that the design for both of new room types would meet the patients' needs and was operationally efficient. DMUs helped users discuss with the design team their suggestions on how to improve the new room types.

Table 2. *Cont.*

Type of Mock-Ups	Authors	Purposes/Issues Addressed	Phases	Data Collection Methods	Outcomes/Achievements
Both	Leicht et al. [37]	A DMU of the pharmacy of a medical office building, to review the detailed design The on-site PMU just to offer the opportunity for different feedback from the DMU	Construction documents	Observation and questionnaire	The DMU provided an opportunity for all stakeholders to have a review of two focus areas for the pharmacy (the cabinetry/casework and the electrical outlets), the equipment, textures and lighting. The PMU was used for comparison, but no outcome was specified.
Both	Wingler et al. [38]	A PMU and a DMU of an operating room to compare different design communication media in helping clinical staff understand design information	Conceptual design	Interviews and focus group	PMUs may better promote a user-centered design process. DMUs seem less expensive, time-consuming, and labor-intensive media to support clinician engagement. However, DMUs may not be as effective for clinician evaluations of functionality.

In Table 2, 15 cases used the PMU simulation, two used the DMU one, and four incorporated the PMU and DMU simulations into the same study. The literature suggests that PMU and DMU simulations can effectively support the clinical staff's understanding of proposed design information. Both simulations are favored in all the hospital design and development phases. Table 2 suggests that the purposes of using PMU and DMU sessions are similar.

As indicated in Table 2, a PMU can discuss the conceptual design ideas in the early design process [5,8,32,38]; evaluating or testing various design aspects and details during the schematic design and design development phases. It can also be applied before the construction phase (i.e., construction documents) or after occupancy [5,6,8,12,13,32,33]. Particularly it can help decide or review space requirements, optimum clearances for operations, room configurations, room size, room volume, and the functional arrangement of furnishings [4–6,8,17,32–34]. It can also inform the design considerations for reducing patient falls or the risks of occupational injuries among the clinicians [7,9], promote EBD solutions, or develop design guidelines for the whole design process [4,17,34]. Reflecting on Table 2, it suggests that many more studies on PMUs than on DMUs have been identified through various academic or non-academic publishing channels.

Table 2 shows that DMUs can be used through the whole design process to discuss or review detailed design aspects, such as the mobility, location, visibility and type of medical equipment and furniture, the accessibility, flexibility, safety, size, and shape of clinical rooms [5,32,36–38]. It appears that a DMU can undertake more mock-up exercises than a PMU. It would be more flexible to allow stakeholders to visualize the design at all the phases of the design process [5,36,37]. Dunston et al. [36,39] suggest that the motivation for DMUs is to replace or supplement the full-scale PMU practices. However, Durham and Kenyon [5] indicate that DMUs cannot simulate care and treatment scenarios within the space. DMUs may not be as effective for clinician evaluations of functionality [38].

Other studies show much evidence that there are similar features of the DMU applications in the other industries [40–45] and some successful practices relating to the integration of PMUs and DMUs (prototypes) in product development [43,46–48]. However, detailed information is still lacking in relevant literature about the applications of the DMUs and the integration of PMUs and DMUs in healthcare building design and development compared to the other industries.

The data collection methods used in PMU and DMU simulations are similar, including observations (with the help of video recording), feedback, interviews, questionnaires, workshops, and focus groups. Many studies used more than one method to help in data analysis with information obtained from different sources.

The literature in Table 2 indicates that most PMU simulations were used to collect and analyze data rigorously. The mock-up sessions were well structured and controlled for the experimental exercises, so testing, examining, or evaluating the simulated areas could be recorded with the empirical data [4,6,8,9,12,13,33–35]. According to Hignett et al. [4] and Colman et al. [35], defining an example to test, developing a test scenario, and following a test guide or protocol are the essential steps for conducting a PMU simulation and obtaining the tangible data effectively. Some literature shows that a mock-up simulated many task scenarios but provided little information on the data and the simulation process. It suggests that the results might be unreliable.

Table 2 and other literature suggest that DMU simulations were adopted to provide a visual perspective of the simulated areas or approve the final design solutions (probably with some minor modifications) [5,10,32,36–39,44,47,49,50]. However, little literature describes how the data were collected and analyzed by using DMUs. The limited information about how participants performed in a DMU exercise indicates that DMUs cannot easily accommodate multi-participants' performances and simulate complicated activities [5,10,32,36–39]. Meanwhile, physical information, such as the dimensions of a room or space, could not be collected or measured physically and accurately. No literature has detailed the data collection and analysis process of integrating PMUs and DMUs.

4. Discussion

4.1. PMUs vs. DMUs

Mock-up simulation within the development of healthcare facilities is one of the participatory ergonomics methods [18,20], involving various stakeholders in the testing and reviewing of potential design solutions in order to achieve desirable goals.

According to the results and other relevant literature, there has been much evidence to demonstrate that PMUs have been extensively and successfully used for design evaluation and staff training, with few successful applications of DMUs in the healthcare sector [4–13,16–18,20–23,32–34,36–39]. Compared with DMUs, PMUs may be easier to help the hospital users understand the design process and evaluate their expectations in the healthcare building planning/design and construction phases [5,38,51–53]. PMUs can allow people to fully experience the size of a room, in which they can touch, move around, and respond to a space that they fully understand. Some researchers suggest that a PMU simulation is more suitable for small applications or a part of organization needs, as it is time-consuming and less flexible for change [5,38]. Currently, the typical hospital design and construction processes are so fast that many decisions have to be made quickly rather than spending time on the construction of PMUs. Documenting and then modeling the many specialized types of equipment and fittings with interactive features also take time. A DMU can make this process simpler and quicker. It is more flexible to create or change than a PMU, and can undertake more experiments [5,36,37].

Studies suggest that participants in a DMU usually need to be trained first to perform correctly in a virtual environment [5,38]. Moreover, some researchers suggest that spatial requirements for clinical activities, such as the clearance for operations, space layout, room size, and the functional arrangement of furnishings, need to be tested or reviewed in a PMU exercise rather than in a DMU one [5,18,38,54–56], as the latter cannot accommodate care and treatment activities physically, and ensure the spatial requirements are appropriately measured [5,10]. For instance, a room or space with an optimal layout with correct dimensions will be achieved only by PMU exercises by carefully simulating clinical activities.

In recent years, more research has been paying attention to environmental qualities that consider the end-users' psychological, social, and spiritual needs [57]. The biophilic design supports the connection between people and their environment and enhances human functioning and health by establishing nature-informed habitats for people to live and work in [57–61]. Its principles have been advocated and applied in the healthcare facility planning and design to improve patient outcomes and reduce staff stress through a healing and supportive environment. The design attributes extracted from the biophilic design approach include water, plants, natural materials, specific forms, shapes, motifs, and proportions from the natural world [59,60,62]. This paper suggests that DMUs will be suitable to test and review the variable attributes in the design phases to enhance users' health and well-being.

PMU and DMU simulations can be conducted using qualitative and quantitative methods such as observation, feedback, interview, questionnaire, workshop, and focus groups. We suggest that PMU and DMU simulations should focus on different issues to be addressed (Table 3). As it is especially suitable for looking at spatial requirements, a PMU would be better to be adopted in the phases of design briefing, conceptual design, and schematic design. A DMU would be more suitable for most hospital design and development phases.

Table 3. Key issues to be addressed by using PMUs and DMUs.

	PMUs	**DUMs**
Issues to be addressed	Room size, clearance for operations, room volume, patient safety and privacy, patient and family expectations and preferences, clinical activities such as manual handling, lifting, transferring, equipment/furniture arrangement, optimal layout, headwall, storage, position of en-suite, accessibility, infection control, and so on.	Room lighting, hand washing compliance rate, walking distance, staff planning; clinical productivity, staff work areas in a patient room, equipment/furniture, texture, storage, layout planning and evaluation, architectural features for infection control, patient capacity, bed capacity management, assessment of noise levels, emergency preparedness, biophilic design elements, and so on.

The costs for PMUs ranged from less than US dollars 100 to about USD 1 M depending on the number of different types of mock-up rooms and materials in a project [5,23,55]. PMUs can be built up with completed finishes and furnishings representing the actual design for demonstration and display. Therefore, they will be costly in terms of initial construction expense, costs associated with making modifications through a reviewing process, and the final demolition and disposal costs. The potential cost savings by using DMUs instead of PMUs is compelling. However, not only such direct costs should considered. The PMUs are always built up for a few specific or typical rooms, which should be highly repeated in a project, and may affect many clinicians and deliver a large percentage of patient contact, such as patient rooms. A well-run PMU simulation can help develop a decent design with optimally sized, furnished, and equipped rooms or spaces. This will positively impact the patients' treatment, staff efficiency, and safety, which should lead to cost savings in a building lifecycle eventually. Moreover, as mentioned earlier, expensive mock-ups may not be needed for design or evaluation, as long as the layout and dimensions of a mock-up closely represent the actual design being tested or evaluated. Inexpensive, lightweight materials enable different scenarios to be easily and quickly tested. It can achieve optimal design solutions.

4.2. Limitations of Using a PMU or DMU Simulation

Although mock-ups would be built up with the same layout and size as the actual design, they will never fully represent the real world. Within a PMU comprised of lightweight equipment and furniture, it has been found that the participants might still not be able to perform the tasks manipulating those simulated elements/components with the same effort and posture as they did in their workplace [5,18,22,37]. Another issue is that participants might not have the same emotional response when performing a mock-up task compared to a real task at their workplace. For example, a nurse usually performs a real resuscitation task with highly emotional stress [63]. However, as a participant in a mock-up process, he/she may have performed this task without any pressure. This may lead to neglecting some procedures or actions which may affect the physical environment. This is one of the general limitations of mock-up simulations. It would be ideal for building a PMU in a real clinical environment with the actual equipment/elements to give the clinicians a more realistic setting.

For a DMU, it would be necessary to train the participants to use the digital tools properly [10] and gather their biometric data (i.e., heart rate, respiratory rate, blood pressure, galvanic skin response) during DMU simulations [10,39]. This could help quantify participants' emotional responses to the virtual reality simulation and compare this with PMUs and the actual finished products.

5. Conclusions

The paper has discussed PMU and DMU applications in healthcare building development. PMU simulations usually allow human sensory evaluations of a product. Due to time and cost issues, PMUs are more suitable to be built up in a few specific rooms, which may affect many clinicians and host a large percentage of patient contact, for example, patient rooms. A DMU is easier to set up and takes less time than a PMU. With reasonable cost-effectiveness and flexibility, DMUs of the hospital layouts can set up infinitely different task scenarios and allow limitless users to evaluate room designs through a virtual environment. The two types of technologies should be complementary to each other. The strengths and advantages of one will address the weakness and limitations of another one.

Mock-up simulations have become an essential aspect of EBD with qualitative and quantitative research methods that can form a powerful mechanism for effective and efficient healthcare design and development. PMU and DMU simulations can identify and solve design problems before a hospital is built. They will speed up the design and development processes as quicker feedback can be collected from the users to lead to a user-centralized hospital.

Healthcare building designs present very different challenges to other types of buildings. It would be essential to the success of a mock-up to choose appropriate methods, structure the methodology, and control the mock-up sessions. A well-conducted mock-up simulation can generate more reliable evidence-based (rather than the so-called "the professional experience-based") information that architects, healthcare planners, project managers, contractors, and other stakeholders can rely on. Such information will help them better understand clinical functions, care delivery systems, and clinical staff involvement, finally promoting design quality.

6. Theoretical and Practical Implications

- The clinical staff's involvement is essential for mock-up simulations to facilitate their performing of specific tasks, which will help architects understand how the care model affects the simulated area in order to produce optimal design solutions.
- The healthcare design practitioners should be able to apply both PMU and DMU technologies and have the ability to select the appropriate one for some mock-up exercise or to combine their strengths. It increases the need for the integration of PMUs and DMUs. With the development of virtual reality visualization technology, especially immersive virtual reality technologies with various equipment, such as VR helmets and gloves, it is expected that the DMU techniques and methods will be improved signification.
- DMUs would be suitable to contribute to the biophilic design by testing and reviewing the variable design attributes in the design phases to enhance end-users' health and well-being.

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