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The Digital Twin Immersive Design Process and Its Potential Disruption to Healthcare Design through a User-Centered Approach

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Abstract: This applied research proposes a solution to the static government design process for Thai healthcare architecture to better serve the needs of its elderly society. In its place, a novel real-time design process, termed the Digital Twin Immersive Design Process (DT-IDP), repurposes aspects of digital twin and virtual reality technologies into a 'unitary' immersive design system. This system accesses 'experiential' user-centered data, helping enhance the design of Thai healthcare space beyond a standardized government response. This text builds a rationale for departing from the current design process by describing the formation and advantages of the DT-IDP process. To test its credibility, the DT-IDP process is used to build and compare two digital versions of an existing healthcare space. In these spaces, participants are immersed (elderly patients n = 30; nursing staff n = 5; government healthcare architects n = 5) to assess visitor experiences based on daylighting, artificial lighting, and views of nature. Following immersion, government healthcare architects are interviewed in-depth to evaluate the process's efficacy and their willingness to adopt it. Results confirm the potential for this process to capture 'user-centered' insights, otherwise unobtainable without immersion. Consequently, healthcare architects express a unanimous preference for DT-IDP, acknowledging its unique capacity to bridge a market gap through an experiential component that could better assist them in creating a superior final product. Ultimately, they assert that demand for these features could have a disruptive impact to the current healthcare design process, helping to re-envisage the design of future Thai healthcare space.

Keywords: digital twin; user-centered; VR immersion; healthcare design; design process

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1. Introduction

This article proposes the development of a novel 'dynamic' architectural design process termed the Digital Twin Immersive Design Process (DT-IDP). This process emerges through 'applied' research [1], attempting to directly apply research findings toward immediate solutions. It is undertaken in response to the anticipated burden placed on Thai healthcare by an increasing elderly society, one showing alarming levels of non-communicable disease (NCDs), i.e., hypertension, diabetes, cancer [2]. With Thailand soon to enter 'super-aged' society status, its healthcare infrastructure appears ill-prepared to deal with this anticipated demand from the elderly and must be accelerated, to produce accomplished age-friendly healthcare spaces.

The DT-IDP aspires to the enhanced design and performance of healthcare space. Its uniting of digital twin software (the ability to create highly accurate replicas of real-world space) and immersive technologies (the ability to enter into these replicas virtually) aims to provide future elderly patients—and accompanying nursing staff—with healthcare environments that minimize stress whilst delivering quality care. Tackling this escalating issue is of utmost urgency for Thai government healthcare [3–5]. Should these concerns

remain neglected, public trust in the government healthcare system could likely erode as an escalating elderly patient population pushes the healthcare system to point of failure.

1.1. Uniting the Potential of Emerging Technologies

The integration of digital twin and virtual reality immersion as part of a 'unitary' architectural design process remains underexplored. A meta-analysis by Prabhakarn, [6] shows no specific unitary development with its uses limited to ideation [7] (p. 103). This research attempts to utilize these technologies to shift the Thai healthcare design process towards 'user-centered' design feedback and evaluation, markedly improving end-user satisfaction with healthcare space [8] (p. 36) [9,10].

Pursuing this shift looks to 'Human-centered Design' and 'Design Thinking' processes currently employed in the industrial design sector. These processes are driving a profound understanding of the end-user and their human needs. In particular, the status of design thinking has been elevated through its ability to rapidly access end-user needs and desires [11]. It provides a collaborative, non-linear design approach, whose five stages (1—empathize; 2—define; 3—ideate; 4—prototype; and 5—test) reveal a rapid, highly effective procedure for attaining valuable user-centered data to steer design projects [12,13]. This shift, away from expert-oriented input towards the immersive contributions of non-expert end-users, anticipates a "humanization of healthcare facilities" [14] (p. 34).

1.2. User-Centered Gap in Healthcare Architecture in Thailand

The need to humanize healthcare architecture (via age-friendly and age-sensitive spaces) exposes a 'user-centered' gap in the design process, one able to be taken up by the DT-IDP. Figure 1 indicates what is required to transition from the prevailing static linear design process (lower-left quadrant), towards the novel real-time, user-centered, non-linear DT-IDP (upper-right quadrant).

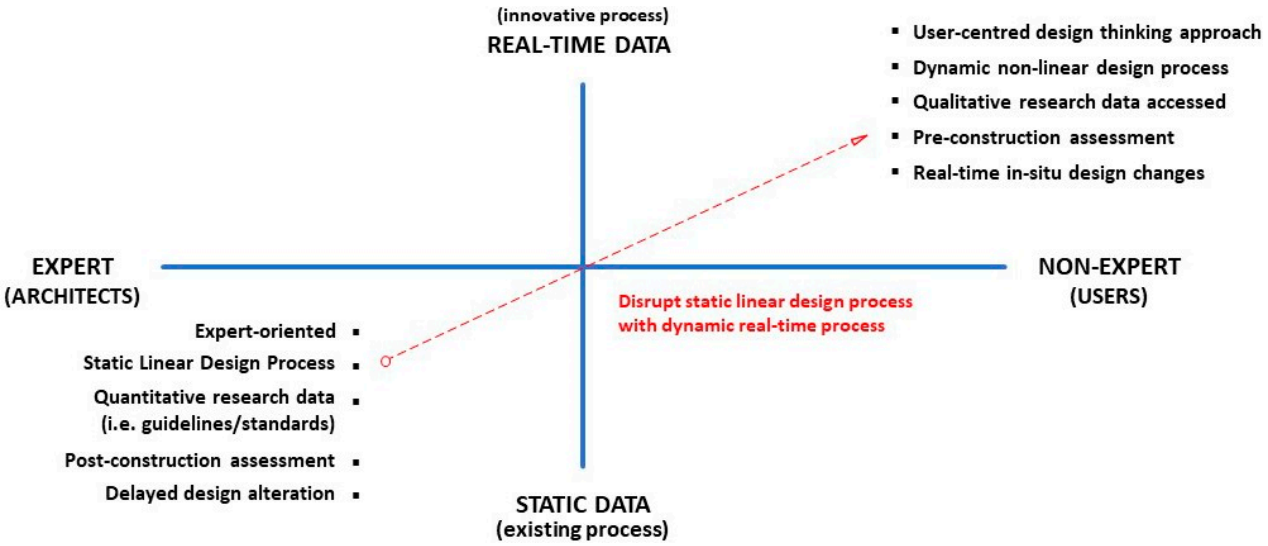


Figure 1. Transitions from existing design process to DT-IDP.

The DT-IDP aims to dynamically re-model healthcare architecture's current design process by driving transformation of its longstanding architectural conventions (i.e., reliance on 2D and 3D visualization techniques, standardized expert data guiding design, post-construction evaluation) that now appear outdated and inefficient. Ultimately, it seeks to work 'immersively' with non-expert end-users, directly from within the space being designed. Such engagement is expected to result in higher quality future healthcare space via 'user-centered' insight, otherwise unachievable using traditional design means.

2. Literature Review

Annemans [15] asserts that while there is no longer a shortage of research in healthcare building design, the challenge lies in effectively translating research into practice (p. 2). Even with this rising volume of literature, a disconnect persists between research and its practical application [16]. In this sense, research synthesizing advanced technology into a standardized unitary workflow for architectural practice remains under-investigated, lacking detailed discussion about the advantages and limitations of an approach for use by architects themselves. This knowledge gap undermines the potential of immersion to engage critical 'end-user' insight in the design of healthcare environments that meet the complex needs of both patients and providers.

2.1. Challenges for End-User Feedback with 2D, 3D, and Immersive Space

The desire to involve end-users (i.e., patients, nursing staff, medical professionals) in the design of healthcare space remains problematic. Sateei [17] articulates the ineffectiveness of 2D drawings and 3D models to provide end-users with sufficient spatial understanding (p. 2). Roupe, as cited in Sateei [17], shows that two-dimensional drawings place "high cognitive demand" on end-users, who, as 'non-experts', can lead them to misinterpreting drawings, ultimately preventing their involvement in the design process [18] (p. 8).

End-user feedback has been routinely obtained through non-immersive methods such as interviews and surveys strategies [19]. These methods fail to rival immersive visualizations, which provide a superior description of space over-and-above visual imagery [20]. The successive advance from two dimensions to three dimensions—and onto immersion—allows for the decisions (taken by architects) to be "well-informed" [21] (p. 78).

Progressive attempts have been made to better engage end-users in the design process and capture their qualitative data 'virtually'. In earlier methods of immersion, architects built their understanding of a space through 1:1 lab-based environments, utilizing diverse projection and visual media. These physical constructions were not however considered "fully-generalizable to real-life contexts" [8] (p. 27). Examples from the early 2000s show the emergence of the cave automatic virtual environment (CAVE). As 1:1 full-scale immersive environments, CAVEs allowed for "dozens of people to share immersive content simultaneously" [22] (p. 349). More recently, research efforts to access qualitative end-user feedback has seen the creation of "fully-immersive virtual environments" (FIVEs). Immersive research into the capture of end-user data through FIVEs has included emergency clinics [23]; the operating theatre [24]; hospital wayfinding [25]; hospital cafeteria [26]; waiting spaces [27]; and the healthcare workplace [28]. The use of FIVEs has facilitated better end-user involvement and subsequent design analysis [8] (p. 28).

The most contemporary digital environment open to immersion is the digital twin (DT). The potential of the DT lies in its ability to perfectly imitate 'real-world' conditions, prior to any physical counterpart ever being built [29]. Although the intersection of DT with VR immersion is in ascendancy, a meta-analysis by Pirker et al. [30] reveals that within architecture, DT/VR integration still remains limited in use, currently restricted to extending the performance of BIM (i.e., [31]).

2.2. Generating Unforeseen Information

In the absence of qualitative 'user-centered' data, architects continue to rely on their expertise and past experiences to create new spaces "with no evidence the experience is transferable" [32] (p. 418). Healthcare architects typically default to their own preferences, rather than to the experiences of those for whom their building is being designed. The traditional process "disregards the opportunity to implement 'unconventional' design, informed by other stakeholder input, especially the patients" [32] (p. 419). It 'guesses at' the functional needs of end-users, resulting in generic healthcare spaces, arrived at through over-reliance on quantitative data from standards and guidelines. Buse et al. [33]

(p. 1436) emphasizes the importance of architects being cognizant and empathetic with how eventual users will inhabit space.

Instead, architects continue to draw from personal experience, using their own bodies as reference [34] (p. 57). They envisage themselves as potential users of their as-yet-unbuilt spaces, based on past experiences of occupation. In Buse's research interviews, architects acknowledged that designing for end-users requires they "step into the shoes of such users (Interview 7, p. 1441). One architect stated, "I always try to put myself in someone's shoes" (Interview 8). Yet another declared that "when this latest scheme is finished [. . .] we're going to [. . .] get in a wheelchair and wheel ourselves round the building and see how wheelchair-friendly it is" (Interview 3). Within the field of healthcare design, achieving authentic empathy and understanding with end-users is seen as a critical requirement for attaining high standards. Empathic and emotion-oriented work in medical design is in growing demand [35,36]. Unfortunately, this potential is neither achievable, nor an aspiration of the prevailing traditional design process for Thai healthcare architecture.

In contrast, the advantages of the DT-IDP (via first-person PoV immersion) allow for end-users to create data by freely navigating within digital replicas. The ability for their behavior in space to be recorded for in-depth analysis via big data analytics becomes realizable [37–40]. Rather than 'guessing at' the experiences of their end-users, healthcare architects can now obtain data vicariously through the elderly, assimilating their healthcare space experiences toward design. The architect accesses the direct visual, temporal and locational experience undertaken by an elderly hospital patient/visitor. Moreover, immersion can allow for architects to situate themselves within a virtual space, borrowing the position, vision, and even the disabilities of a patient [41] (p. 2/37) [42] (p. 031013-5). Resulting data could then be used to inform speculation on new design trajectories inspired by end-users themselves. In essence, the use of the DT-IDP will allow for architects to freely enter their DT replica at any stage (schematic, design development, bidding, construction documentation, etc.) to experience and verify the functionality or aesthetics of a space being proposed. These newly enhanced spaces (informed by the qualitative experiences of immersed end-users) are expected to better fulfil the spatial needs of future occupants. In this way, first-hand 'user-centered' experience directly enhances healthcare space.

2.3. Rationale for a Shift to DT-IDP

Through applied research, a rationale for the use of the DT-IDP was progressively established. Researchers hypothesized that its advantages would supplant the prevailing design process, one clearly underperforming due to the following inabilities:

- Consider 'user-' rather than 'expert-oriented' opinion to inform the design of healthcare architecture;
- Engage with immersive 'experiential' data;
- Detach from a linear design process with slow decision-making capacities.

The novel DT-IDP was created to provide the following counterpoints to the above problems:

- A user-oriented approach with data elicited from end-users to inform design;
- Access to qualitative 'immersive' data beyond 2D and 3D representations;
- A non-linear design process with 'immersive verification' to support rapid decision-making at differing points in the process (design, construction, bidding stages, etc.).

Existing research shows that when compared to VR immersion, reliance on traditional 2D drawing and 3D modeling is less persuasive and limited in achieving a comprehensive understanding of space [43] (p. 2/23). Instead, immersion allows for users to interact with space more effectively, providing richer, more nuanced feedback. As technology continues to advance, VR immersion is able to extract increasingly detailed and actionable data, underscoring a superiority over more traditional representational conventions [7,44]. These advantages coalesce to underpin a rationale for a more synthesized, unitary design process for healthcare architecture, circumventing traditional design strategies that gravitate towards rudimentary

hospital design and a lack of patient-centric concerns within healthcare spaces—potentially compromising elderly patient health and safety and staff productivity.

2.4. Contrasting New and Old Processes

Figure 2 compares the DT-IDP to the traditional approach predominating in government healthcare architecture in Thailand.

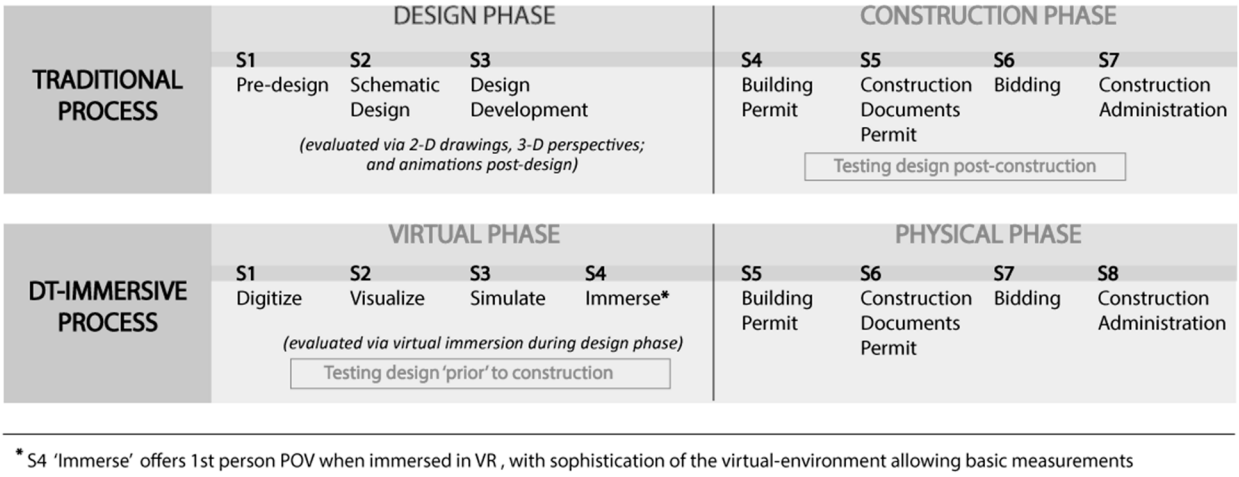


Figure 2. Comparing traditional architectural design process with the DT-IDP.

In the diagram, the 'TRADITIONAL' architectural design process is typically divided into a DESIGN and CONSTRUCTION phase. It operates via long-established conventions, namely, 2D plans, sections, elevations, perspectives, 3D renderings, animation/fly throughs, physical-scale models, etc. [45].

In contrast to this, the DT-IDP is divided into a VIRTUAL and PHYSICAL phase. It is a 'unitary' design process, providing an 'immersive' tool—within a single integrative design process. Through it, 'non-expert' users (i.e., ageing patients and/or nursing staff) are enabled to provide valuable 'experiential' data and decision-making feedback for the architect. These influential data inform a design proposal through real-time immersive evaluation, with design alterations made whilst immersed.

The VIRTUAL design phase (S1–S4 above) thus supersedes the traditional version by; (1) an ability to prioritize 'real-time' immersive engagement over 2D and 3D representation; (2) elevating 'non-expert' data to inform the design and performance of a proposed space; and (3) enhancing both the quality and certainty of decision-making by immersive verification. In this way, a real-time, user-centered approach is opened up, placing the qualitative insights of end-users at the epicenter of data collection and spatial analysis. Researchers propose these differences contain the potential to disrupt the traditional governmental design approach for Thai healthcare architecture. By establishing a 'VIRTUAL' design phase, immersion is promoted over 2D and 3D representation as a new design and evaluation component.

2.5. Repurposing Technology: A Four-Stage Novel Design Process

Through an applied research process, the researchers looked for the best way to engage disparate technology on the market to directly repurpose it. The researchers initially pushed for the development of the DT-IDP by engaging DT capacities from the industrial engineering sector (Figure 3).

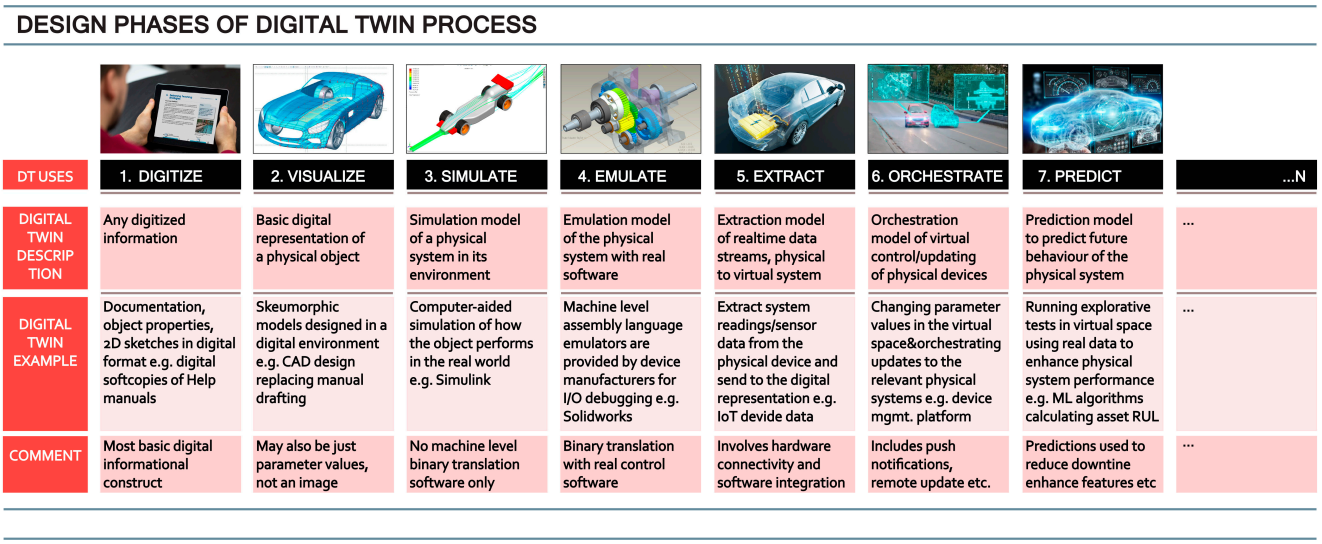


Figure 3. The innovative capacity of the digital twin (Source: IoC Analytics, 2021 [46]).

Within the industrial sector, the capacities of the DT are divided into seven stages. Through repurposing, the DT-IDP adapts its initial three stages as a foundation for a potentially new architectural design process. Table 1 itemizes the repurposing of these stages:

Table 1. The shift from an engineering to architectural design domain.

STAGE	ENGINEERING DOMAIN	ARCHITECTURAL DOMAIN
1_DIGITIZE	Document all 'object properties' into a digital format.	Digitize all properties of the building/interior space.
2_VISUALIZE	Create basic D representation of the engineering object.	Create a virtual model of the building and/or interior space.
3_SIMULATE	Simulate the object's real-world performance (temperature, stress conditions, energy consumption, etc.).	Simulate the real-world conditions of the building and/or interior space (temperature, light, views of nature, energy consumption, etc.).

2.6. Immersion: An Effective Complement to DT Technology

In addition to these initial three stages, a fourth stage entitled 'IMMERSE' was added. The synthesis of all stages is shown in Figure 4. In this stage, untethered head-mounted VR technology was adopted to achieve end-user immersion. The potential for the DT-IDP to collect real-time, user-centered data via 'experiential immersion' provides healthcare architecture with a dynamic, real-time, user-centered design method, able to access hitherto untapped user-centered data from potential future users (elderly patients, young children, nursing staff, people with disabilities, etc.) to heighten the architectural quality of future healthcare space.

Figure 5 shows a detailed description of the VIRTUAL phase (S1–S4). This same virtual phase is also shown embedded in a larger formalized version of the DT-IDP below (see Figure 6) depicting the VIRTUAL phase (S1–S4), PHYSICAL phase (S5–S8), and DT phase (S8+).

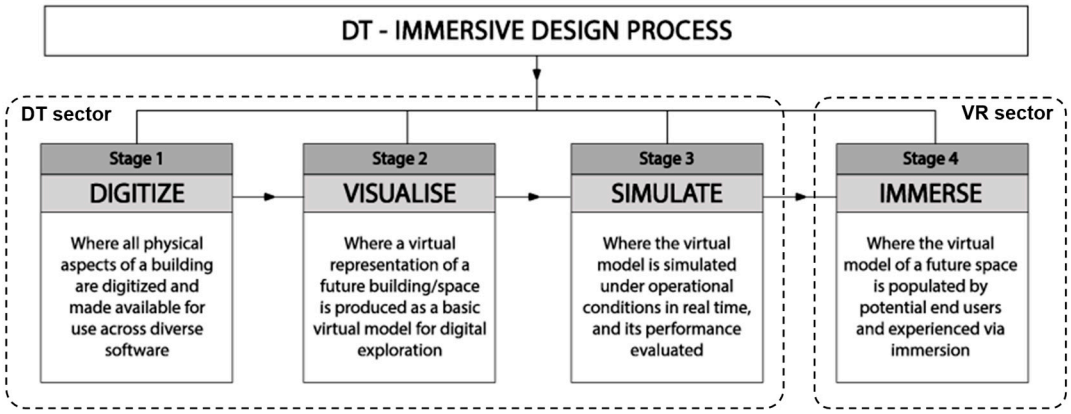


Figure 4. The 4-stage DT-IDP for healthcare architecture.

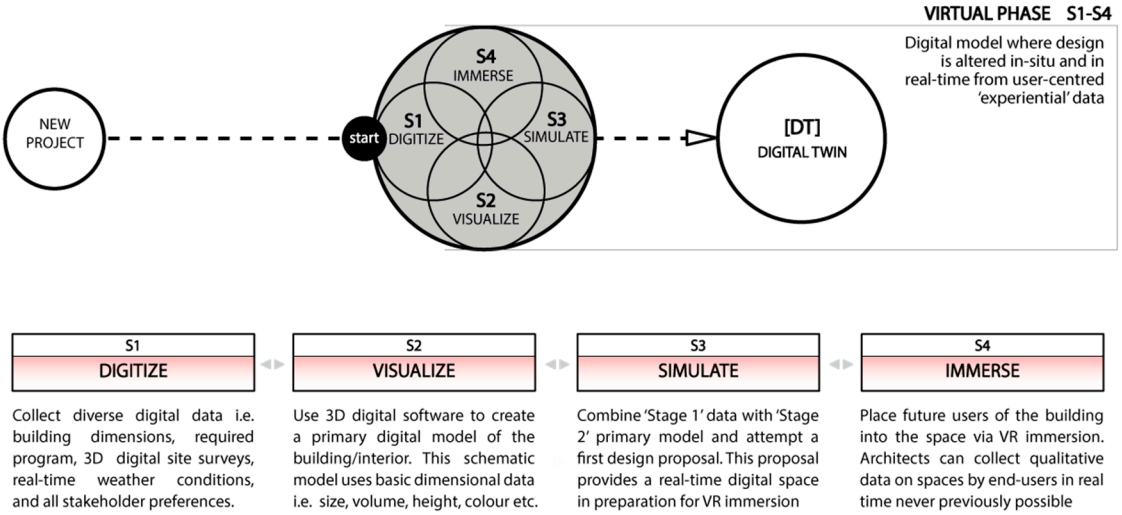


Figure 5. Virtual phase (S1–S4) of the DT-IDP.

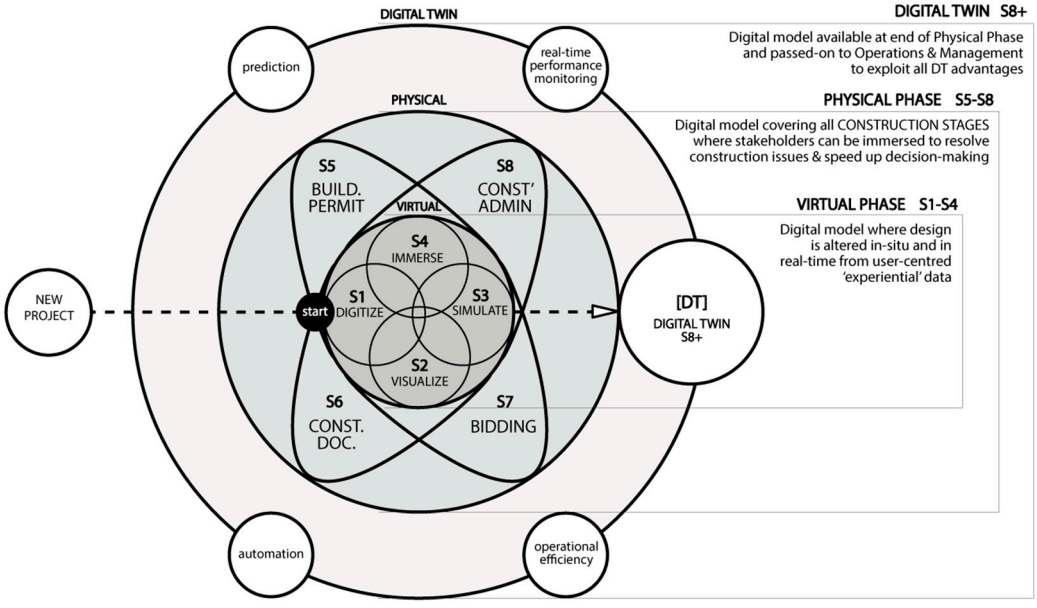


Figure 6. Overall scope of the DT-IDP under research.

3. Methodology and Materials

The development of the DT-IDP process engaged an 'applied research' methodology [47]. Through cycles of experimentation, adaptation, and evaluation (with both software and hardware), a unitary and user-friendly process was refined, eventually emerging as the DT-IDP. This approach was underpinned by a series of systematic experiments designed to explore the compatibility between physical technology and digital software systems. This iterative methodology ensured the convergence of hardware and software and eliminated software/hardware conflicts. With each cycle of prototyping the design process was further tested and enhanced through specific software and hardware alterations (i.e., system stability and peripheral compatibility).

Research looked at both 'Hardware' and 'Software' setups incrementally, trialing diverse versions and incrementally adjusting them to ascertain which configurations provided the most effective process. This process was driven by three research criteria, namely, (1) interoperability: where new technology would build on technology familiar to existing research staff; (2) synchrony: where current companies affiliated to researchers would not be unsettled by the introduction of new technology; and (3) futurity: where newly emerging technology from research should be absorbed into the existing office terrain for researchers. Conformity to these criteria attempted to ensure the simplest path for DT-IDP integration into the existing office fabric of Thai healthcare architects.

3.1. DT Immersion's Technological Setup: Hardware Selection

An array of technological equipment with which to build a preliminary digital twin with immersive capabilities was shortlisted, configured, and refined (Figure 7).



Figure 7. The DT-IDP's technological setup including hardware and software.

This selection of hardware emphasized cost-effectiveness and practicality. The Oculus II (equipped with a linking cable) was identified as a budget-friendly option for VR integration. To capture existing healthcare environments, the RICOH C1 360 camera was utilized, as it provided an easier and less complex solution compared to LiDAR systems, at a fraction of the cost. Its seamless integration with Matterport's online software v.3.0 (able to stich images together into a seamless immersive environment) enabled rapid immersion into captured spaces through a highly cost-effective subscription. Central to the DT-IDP hardware setup was the Lenovo ThinkPad (11th Gen Intel(R) CoreTM i7-11800H @ 2.3 GHz). Recognized as a leading option at the time, this laptop was chosen to ensure optimal system performance,

through which immersion could be monitored and controlled. In addition, a second external Lenovo monitor (linked via high-speed connection cable) was required to show the built 3D model, through which real-time design alterations to a DT could be conducted. Attached to the ThinkPad (via Oculus cable) was the untethered Oculus Quest 2 (whose connection required 5G technology, and thus an iPhone 14 as minimum spec for connectivity).

3.2. DT Immersion's Technological Setup: Software Selection

Similarly, a shortlist of digital software was investigated. Software selection for the DT-IDP was based on interoperability, cost-effectiveness, and the existing skillset of architects in the Thai market. The interoperability existing between Revit and AutoCAD (via similarity of interface and menus) allowed for a natural progression from 2D drawing to 3D modelling. For the added shift to immersion, Twinmotion was preferred over other industry software (e.g., Enscape, Unity, Lumion) due to superior rendering quality and being optimized for 'real-time' rendering updates. This provided a compatibility across software for seamless integration of workflow. The final criteria for software selection are described below (Table 2).

Table 2. Software/hardware finalization for the DT-IDP.

Software	Features	Selection Criteria
a_BIM 360/Revit	Cloud-based construction management platform, streamlining workflow across different disciplines, i.e., architectural, structural, mechanical, and electrical engineering	• Consistency in interface allowing for productive transition to new software packages • Interoperability as coordinated seamlessly with the 360 BIM platform • Able to design, model, and analyze architectural designs through numerical intervention
b_Dynamo	Open source visual programming plug-in for Autodesk, Revit	• A node-based design environment aligned with BIM/Revit • Numerical data inputted via .CSV file types and subsequently manipulable with tremendous control and accuracy
c_Oculus/Twinmotion	A virtual reality (VR) headset developed by Reality Labs, integrated with real-time 3D immersion software	• Seamless integration between BIM model and VR experience • Untethered all-in-one system • Real-time 360-degree rendering

3.3. Implementing the DT-IDP to Test Validity

Figure 7 above shows the technological setup finally selected for the collection of real-time, end-user data via DT-IDP. In addition to this, the following sequence of images (Figure 8A–F) highlights how 'end-user' preferences are tailorable in real-time, providing an immediacy to design solutions.

In the array, the top-two images show the manual interface through which design changes are implemented. The two center images show changes implemented to the flooring in the interior space. The bottom two images show alterations to the wall and column coverings.

All design alterations were prompted by in situ end-user feedback, and empirically confirmed whilst under immersion. By engaging in these immersive advantages, governmental healthcare architects will be able to exploit user-centered qualitative data—in place of standardized architectural responses—to heighten the quality of Thai healthcare space.



Figure 8. Upper set (**A**,**B**)—interface system; center set (**C**,**D**)—in situ real-time floor alterations; lower set (**E**,**F**)—in situ real-time wall alterations.

3.4. Formalizing the Four-Stage Process: An Architectural 'Pilot Project'

In alignment with applied research, an architectural 'pilot' project was next conducted to test the immersive capabilities of the novel 4-stage DT-IDP process. The selected test site for this pilot project was the Kaset Pattana OPD clinic (Bang Phaew, Thailand). This facility exhibited highly specific characteristics that aligned with our research interests by specifically providing the following:

(a) A current healthcare program dedicated to the well-being of an elderly patient population;
(b) A healthcare facility managed through a 'governmental' administrative model;
(c) An outpatient department serving as a one-stop service for the elderly, currently in need of refurbishment.

Regarding pilot project participants, several factors influenced the sample size. The available pool of 'ELDERLY' participants (fitting the required criteria, i.e., over 60 years of age; with pre-existing NCDs; consenting to participate) was limited by outpatient availability, with researchers locating a final cohort of 30 eligible patients. With respect to 'NURSING STAFF', sample size was determined by availability and consent, leading to a total of 5 eligible participants. In addition, five government healthcare architects (representing the maximum feasible number available given the specialized nature of the field) also participated. Notwithstanding, this number was sufficient to ensure statistical validity with a 95% confidence level at <0.05 significance. As such, sample sizes remained effective for research purposes.

Execution of the pilot project then followed the DT-IDP 4-stage process developed through research:

3.4.1. Stage 1: DIGITIZE: Collecting Dimensional and Performance Data

In Stage 1, all the existing building's dimensional data at Kaset Pattana (i.e., size, width, heights, aperture locations) and relevant performance data (i.e., daylighting levels, artificial lighting levels, and views of nature) were collected from the OPD to support the creation of a basic DT replica.

3.4.2. Stage 2: VISUALIZE: Creating the OPD Environment

In Stage 2, a DT replica of the Kaset Pattana OPD space was created using Revit software 2023—in tandem with Dynamo/Python plug-ins—providing architects with a highly detailed three-dimensional model, faithful to its real-world counterpart (see Figure 9A–C below).

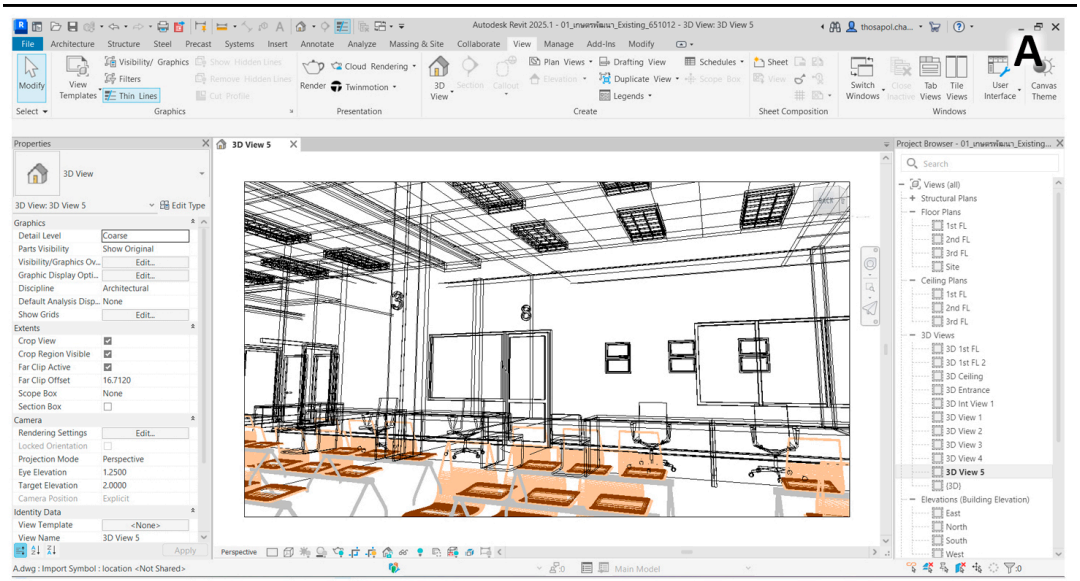


Figure 9. *Cont.*

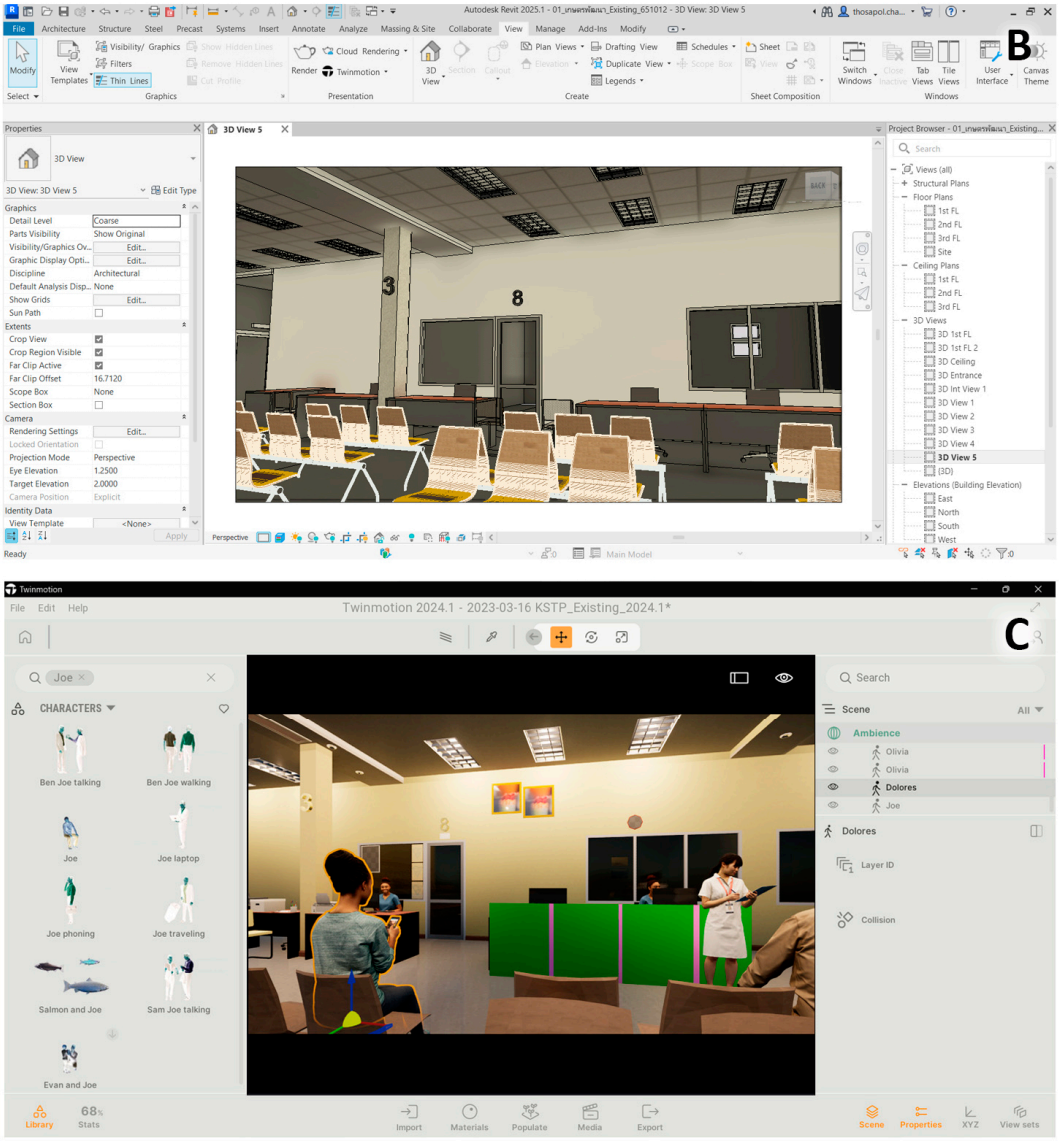


Figure 9. Creating the immersive environment: (**A**) wireframe (top), (**B**) realistic (middle), and (**C**) real-time (bottom).

3.4.3. Stage 3: SIMULATE: Preparing to Evaluate Spatial Performance

In Stage 3, performance data were inputted into the DT replica via Revit, providing a performatively accurate copy of the real-world OPD space (ready to be populated by potential end-users, e.g., patients/medical staff) in real time via Twinmotion software 2022.1. Once this virtual replica of the existing Kaset Pattana OPD was completed, a new version of the OPD space was additionally designed, one providing better daylighting, improved artificial lighting, and inspiring views of nature with which to contrast the existing space.

3.4.4. Stage 4: IMMERSE: Evaluating Design via Virtual Occupation

Stage 4 involved 'user testing' both versions (i.e., existing and newly designed) of the Kaset Pattana OPD space. Both spaces were evaluated by existing patients/nursing staff, where they gauged comfort parameters, verified functionality, and appraised aesthetics. Users provided design feedback during immersion, with researchers directly manipulating model components (i.e., window apertures in the façade via Dynamo's node-based visual programming) to affect immediate real-time in situ changes.

3.5. A Fully Formalized DT Immersive Design Process to Establish Credibility

To fully formalize the DT-IDP, researchers took end-users (i.e., elderly and nursing staff) through the 4-stage design process, successfully contrasting existing and newly designed Kaset Pattana OPD spaces. To establish its credibility for use within healthcare architecture, two questionnaires aimed at assessing how effective the process could be at fulfilling its stated functions were created. These questionnaires collected quantitative and qualitative pilot project data to help draw conclusions regarding efficacy. The emerging results were thus evidence-based justifications, supporting the potential of the novel DT-IDP process as a new and effective design method.

3.6. Assessing Viability of the DT-IDP

Two interview-based questionnaires were created to test the validity of the DT-IDP. Questionnaires used a modified version of the existing HCAHPS survey (Hospital Consumer Assessment of Healthcare Providers and Systems) as a basic guide to their structure and measurement methods [48].

3.6.1. Questionnaire 1: 'NON-EXPERT'

The first Likert-based questionnaire tested the ability to gather real-time, user-centered data from NON-EXPERT users (i.e., elderly patients n = 30; nursing staff n = 5) via immersion. It asked participants to express their preferences between the two OPD spaces based on 3 characteristics, namely, views of nature (VoN), daylighting (DL), and artificial lighting (AL), based on universal design standards.

3.6.2. Questionnaire 2: 'EXPERT'

The second semi-structured interview questionnaire for EXPERT users (i.e., government healthcare architects n = 5) asked participants to contrast the DT-IDP with their existing design process. Participants were requested to indicate whether they considered the novel process preferable, and if they would be willing to switch over to it were it made available.

4. Results

Results validating the DT-IDP are represented in two parts:

Part 1:

Verifies if the DT-IDP can fulfil its functions through immersive testing with end-users, ascertaining if their immersive preferences can be used to inform design.

Part 2:

Verifies if the design potential of the DT-IDP is sufficient to disrupt the current architectural design process for healthcare architecture and influence architects to switch over.

4.1. Results of Questionnaires [Part 1]

Questionnaire 1 was devised to obtain a comparison between the two OPD spaces regarding the following:

- H_1.1A-C: Satisfaction levels between the old and new environment via daylighting, artificial lighting, and views of nature based on universal design standards.
- H_1.2 A-D: Satisfaction levels between the old and new environment based on universal design standards for aging patients with NCDs and differing health conditions.

4.1.1. Comparison of Preferences for OPD Spaces (Quantitative Analysis)

The DT-IDP's viability was evaluated through two questionnaires targeting elderly patients (n = 30) and nursing staff (n = 5 participants). These questionnaires sought participants' preferences between two OPD spaces (one designed using the existing process and the other via the DT-IDP process). The experiment emphasized three critical spatial aspects, daylighting (DL), artificial lighting (AL), views of nature (VoN), all within the purview of universal design standards.

Data Interpretation

The collected data measured satisfaction levels with both of the OPD environments for aging patients with non-communicable diseases (NCDs) and working staff (Table 3).

Table 3. Consolidated table of satisfaction levels.

Hypothesis	Characteristics	Comparison Group	Mean Score (New)	Mean Score (Existing Group)	Significance (*p*-Value)
H 1.1A-C	DL	New vs. existing OPD	Higher	Lower	<0.05
H 1.1A-C	AL	New vs. existing OPD	Higher	Lower	<0.05
H 1.1A-C	VoN	New vs. existing OPD	Higher	Lower	<0.05
H 1.2A	DL, AL, VoN	Male vs. female	Non-significant	Non-significant	≥0.05
H 1.2B	DL, AL, VoN	Different chronic diseases	Non-significant	Non-significant	≥0.05
H 1.2C	DL, AL, VoN	Duration of chronic diseases	Non-significant	Non-significant	≥0.05
H 1.2D	DL, AL, VoN	Age groups	Non-significant	Non-significant	≥0.05

Note: The columns 'Mean Score (New)' and 'Mean Score (Existing Group)' summarize the direction of the results rather than specific values, to simplify presentation. 'Higher' indicates a significantly higher satisfaction score in the new OPD compared to existing OPD, and 'Non-significant' indicates no significant difference in satisfaction scores between comparison groups.

Table 3 above demonstrates the key findings from comparisons (H_1.1A-C-H_1.2A-D) concerning satisfaction levels with daylighting (DL), artificial lighting (AL), and views of nature (VoN) in the new vs. existing OPD environment, as well as the satisfaction levels among different demographic and health condition groups of aging patients with NCDs.

Spatial Satisfaction: Daylighting, Artificial Lighting, and Views of Nature (H_1.1A-C)

In comparing new and existing OPD spaces, the analyses—utilizing paired sample *t*-tests—revealed a statistically significant improvement in satisfaction scores for the new OPD space across all three environmental characteristics (DL, AL, and VoN). This indicates a clear preference for the redesigned space, with significance levels all below 0.05. The influence of spatial factors on participants, particularly 'Daylighting' and 'Views of Nature', significantly enhanced user experience by improving visibility, reducing stress, and promoting a more tranquil environment. These elements were especially appreciated for their contribution to a sense of well-being, with spatiality feeling inviting and supportive. Conversely, 'Artificial Lighting' within the existing space was perceived as inadequate, impairing participants' ability to engage effectively within the space. Collectively, these specific impacts led to a strong preference among participants for the newly designed space.

Impact of Universal Design on Aging Patients with NCDs (H_1.2 A-D): Gender, Chronic Disease Type, Disease Duration, and Age Group Satisfaction

The investigation sought to understand if universal design principles affect satisfaction levels differently among aging patients with NCDs, segmented by gender, chronic disease type, disease duration, and age group. Independent sample T-tests and one-way ANOVAs consistently showed 'non-significant' differences in satisfaction (≥0.05), implying that the universal design effectively accommodates diverse patient needs without compromising satisfaction.

4.2. Results of Questionnaires: [Part 2]

Questionnaire 2 was designed to gather insights from healthcare architects on the advantages and limitations of the DT-IDP process, while also assessing their willingness to shift from a static to dynamic design method. The results are presented as findings in the following section.

4.3. FINDINGS: Questionnaire 1 'NON-EXPERT'

These questionnaire findings illustrate a significant improvement in patient and staff satisfaction in the new OPD setting—executed using the DT-IDP—across all measured

characteristics (daylighting (DL), artificial lighting (AL), and views of nature (VoN)), with satisfaction scores significantly higher than those recorded for the existing OPD space. Further analyzing the data (from demographic and health-related perspectives, i.e., gender, chronic disease type, duration of chronic diseases, and age group) revealed uniform satisfaction levels. These groups showed 'non-significant' differences in satisfaction scores, highlighting the universal design's success in the new OPD space. Such uniformity in satisfaction irrespective of demographic or health status underscores the inclusivity and effectiveness of the redesigned OPD environment, emphasizing that the new space caters equally well to all users.

Results show that the DT-IDP's immersive experience is sensitive enough to discern the 'experiential preferences' articulated by end-users via real-time, user-centered immersion. Participants were able to evaluate spatial characteristics (views of nature, daylighting, and artificial lighting) that would otherwise have remained hidden when using traditional 2D and 3D design approaches. The DT-IDP permits architects to tap into the nuanced experiences of ageing patients and nursing staff, gathering greater feedback to inform the design of future healthcare space.

4.4. FINDINGS: Questionnaire 2 'EXPERT'

Findings from Questionnaire 2 were built on detailed questionnaire responses. Research findings showed the following:

(a) Governmental healthcare architects recognized that the quality of healthcare architecture is currently constrained by an absence of 'user-centered' data;
(b) The ability of the DT-IDP to rapidly access user-centric feedback addresses a gap in the existing design market;
(c) All architects acknowledged the unique experience of 'simultaneity' available via the real-time DT-IDP (i.e., in situ design changes informed by qualitative user-centered experiences);
(d) Architects appeared willing to transition to the DT-IDP, accelerating disruption of the existing design process currently used for governmental healthcare architecture;
(e) Common reservations across healthcare architects include attainment time of the DT-IDP's skillset; transition time to adoption of this new technology; and fixed mindset resistant to a transition to emerging technologies.

These findings show that the DT-IDP possesses abilities demanded by healthcare architects that, in the current design climate, remain unfulfilled. Its ability to access the nuanced personalized experiences of end-users—from within virtual DT replicas—provides healthcare architects with real-time, user-centered data that support a qualitative approach to healthcare space enhancement. Statistical evidence affirms both the DT-IDP's ability to disrupt the existing healthcare design process and provide a missing design component (highly detailed immersion) to potentially enhance healthcare design.

5. Discussion

The DT-IDP holds potentially transformative implications for healthcare architecture and adjacent fields. By synthesizing cost-effective, compatible technologies (e.g., Revit, Twinmotion, Oculus II), the process has the capacity to democratize the design of high-quality healthcare environments. This approach could enable a wider range of architectural practices—particularly those traditionally lacking the resources to invest in advanced technology—to access and implement sophisticated design solutions. Such democratization could accelerate a broader adoption of immersive design technology, potentially improving the quality of healthcare space wherever employed.

The implementation of the DT-IDP into healthcare architecture anticipates changes in disciplinary practices. For instance, the DT-IDP workflow could conceivably redistribute the time architects allocate to design and construction phases. Using 'end-users' to validate design proposals—via immersion—arguably eliminates the need for time-consuming follow-up consultations that collectively increase a project's duration. The abbreviation

of lengthy project timelines is considered a highly appealing factor in the possible uptake of this approach. Moreover, as healthcare architects design alongside end-users in real time—from within immersive design space—a near-instantaneous loop is opened between designing and experiencing architectural space. The immediacy with which a design can be changed using the DT-IDP may represent a more productive and nuanced way to approaching healthcare architecture.

Additional research into the future applicability of the DT-IDP is needed to deepen its potential. Future lines of inquiry could explore the role of the DT-IDP in identifying the unique needs of diverse healthcare environments (e.g., intensive care units, maternity wards, mental health facilities). The process's ability to reveal specific needs could impact patient outcomes, staff efficiency, and overall operational effectiveness within these diverse contexts, contributing to a more comprehensive understanding of each setting's utility. Moreover, modifications to its existing role could see the DT-IDP deployed to test the quality of healthcare environments over time, ensuring they remain functional, adaptable, and beneficial 'as needs evolve'. In this context, the DT-IDP serves not only as an exploratory tool but also as a framework for evaluating spatial changes in healthcare practices. In doing so, the DT-IDP could ensure the effectiveness and responsiveness of healthcare space, with progressive extension into other types of architectural program and their spaces. Such research directions could significantly expand on the insights emerging from this study, widening the DT-IDP's practical application and impact, both within healthcare architecture and beyond it.

Although consensus amongst interviewed architects shows an emphatic desire to adopt the DT-IDP's user-centered methods, obstacles to its transition are also present. One point of contention regards 'age-sensitivity,' in particular, whether 'mature' architectural practitioners (typical to the field due to its required experience) would be willing to pursue the skillset and mindset needed to engage with the DT-IDP. Securing commitment from these architects will likely require further research initiatives. These could feasibly include targeted pilot programs, cross-industry workshops, technological training, leadership talks, and research grants to promote conditions conducive to change.

6. Conclusions

Through applied research [1], a new design approach to Thai healthcare architecture has emerged. The careful search and assembly of the DT-IDP promotes a paradigm shift in the approach to healthcare architecture. Under a single unitary framework, it provides an unparalleled immersive experience that allows for in situ design changes in real time. End-users now have the ability to navigate, interact, and provide feedback in a realistic and intuitive real-time manner, with their 'experiential' preferences and concerns with architectural space instantaneously assimilated into the design process.

When testing the DT-IDP's user-centered approach, healthcare architects asserted that the novel design process exhibited remarkable value. Interview data indicated significant preference for it, over the current traditional healthcare design process. Architects expressed desire to adopt the DT-IDP to counteract the gaps in their current design process (most notably a lack of 'user-centered' qualitative data to inform healthcare design). They unanimously acknowledged the distinctive qualities and benefits it offered (i.e., access to real-time user insight; in situ design changes whilst under immersion; heightening of architectural quality and speed of result). Its engagement could take the design of Thai healthcare architecture beyond mere adherence to quantitative, standardized guidelines and subjective personal design preference. Architects insisted that the DT-IDP's 'experiential' component—accessed through immersion—could better assist them in creating a superior final product, one more effective at meeting the needs of their future users (i.e., elderly patients and nursing staff) and providing them with an improved hospital experience.

Results emerging from the pilot project demonstrated the effectiveness of the DT-IDP in capturing unique design input from each participant concerning daylighting, artificial lighting, and views of nature. Participants were able to articulate specific preferences

and concerns that may not have been fully captured through traditional design processes. Consequently, the findings suggest that an immersive component is critical in humanizing architectural design by ensuring that healthcare space mirrors the diverse and specific needs of its future occupants, particularly as daylighting, artificial lighting, and views of nature play a pivotal role in the psychological well-being of hospital patients and nursing staff.

Questionnaire results affirmed the potential for the DT-IDP to disrupt the current design process for healthcare architecture and chart a new way forward for its future development and evolution. It appeared as a promising design process, underpinning transformation from an expert-oriented to user-oriented methodology and superseding a static design process in favor of a more productive, dynamic one. A potential switch to the DT-IDP is considered by government healthcare architects as enabling future user-centered design insights, otherwise inaccessible through traditional means. Such advantages were shown by research to be sufficiently provocative to cause healthcare architects to transition away from their orthodox process (with which they are well-versed and comfortable using) in favor of a more disruptive technological approach.

As newly emerging technologies (currently driven by new AI initiatives) gain greater interest and traction within design fields, researchers expect the eventual incorporation of these elements into the healthcare architectural design process. In this regard, the DT-IDP developed here should soon expect to face challenges, ones that will either further shape its strengths or make it redundant.

Ultimately, this research endeavored to harness emerging technologies, synthesizing them into a legitimate pragmatic process to mitigate the oncoming elderly NCD dilemma visible on the horizon. What emerged is a unitary design process that the researchers hope will ameliorate the future of Thai healthcare architecture, leading it toward well-designed, cost-effective, age-friendly spaces, for the well-being of a future super-aged Thai society.

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