E-ISSN: XXXX-XXXX, P-ISSN: XXXX-XXXX
Applied Health Administration (APPHA), Vol 1, Issue 1, October 2025, Page: 31-10
https://doi.org/10.69725/appha.v1i1.267

Digital Twin Applications in Optimizing Healthcare Administrative Workflows

Mary Phudit Thai [1], **Aung Shere Ruksat** [1]

[1]*Department of Society and Health, Faculty of Public Health, Naresuan University, Thailand*
[2]*Department of Society and Health, Faculty of Social Sciences and Humanities, Mahidol University, Nakhon Pathom, Thailand*

ARTICLE INFO

Informasi;
Received 17 June 2025
Received in revised form 16 July 2025
Accepted 22 August 2025
Available online 10 October 2025

Corespondence;
Phudit Thai

Keyword;
Value-based governance, Healthcare workers, Organizational efficiency, Patient-centered care

ABSTRACT

Objective: This research examines how digital twin technology improves administrative workflow efficiency by looking at four antecedents, real-time data availability, modeling capability, system integration and staff analytical ability. It also explores the role of prediction accuracy as a mediating mechanism and facility size as a moderator.

Methods: Descriptive statistics of a stratified sample from medical facilities was performed, and data were processed with IBM SPSS Statistics. Descriptive statistical analyses characterized the sample and inferential tests examined associations between variables. The research design focused on both technicalities and humanness in order to understand the sociotechnical aspect of adopting digital twin.

Results: Results indicate that if used in conjunction with staff analytical skills, timely information, sophisticated modeling and integrated systems enhance the flow through workflow. Predictive fit also amplifies the relationships by consolidating the path between our technical inputs and operational outputs, whereas plant size affects the degree to which these efficiencies are accomplished.

Novelty: By combining insights from sociotechnical systems theory, resource-based view, and innovation diffusion perspectives, this study deciphers inconsistent results in prior studies and provides an integrated framework that considers both the technological specificity as well as the firm′s context.

Implications: The findings emphasize the need for cohesive technical infrastructure and employee skills to maximize digital twin benefits. Theoretical and practical implications for understanding digital transformation in healthcare management, as well as implications for managers and policymakers motivated to improve operational performance are offered.

1. Introduction

Health Systems around the world face ongoing administrative inefficiencies in delivering healthcare services and patient care. Delayed data reporting, insufficiently interconnected information systems and the lack of predictive decision-support tools mean longer waiting times, duplicated processes and poor use of limited resources. The experience of Thailand is a case in point. Public hospitals and regional health centers, although the recipient of considerable universal health coverage spending and having a reputation for relatively efficient primary care services, suffer from administrative overload given increasing complexity in patient scheduling down to resource distribution. To address this, the digital twin (DT) concept as the virtual copy of healthcare processes which can replicate tasks, resources and patient flows over time is becoming more popular as a promising solution (Attaran & Celik, 2023; Han et al., 2023). By replicating organizational dynamics and promoting constant surveillance, DT applications have the potential to improve transparency, facilitate predictive analytics, and simplify administrative processes in a manner not possible by using traditional health information systems (Armenta-Garcia et al., 2023; Oulefki et al., 2025; Utku et al., 2023).

E-ISSN: XXXX-XXXX, P-ISSN: XXXX-XXXX
Applied Health Administration (APPHA), Vol 1, Issue 1, January 2025, Page: 32-41
https://doi.org/10.69725/appha.v1i1.267

However, there are severe problems which arises with the use of DT solutions in medical businesses. There is an age old problem around data integrity and the lag in real-time of source data (Gandhi & Prathyusha, 2025; Molina-Solana et al., 2017; Yaqoob et al., 2022). Research reveals that numerous DT implementations within health services are limited by delayed or incomplete data feeds, poor interoperability between legacy systems and low fidelity in real-time data capture (ElArwady et al., 2024; Huang et al., 2021). They reduce the prediction accuracy and erode the staff trust in model predictions which hampers administrative benefits. Above the technical constraints, also organizational and human resources problems prevent from getting this technology absorbed. Inadequate analytical skills have been reported amongst healthcare workers, including managers and auxiliary staff to interpret simulation results or apply forecasts to day-to-day decision making (AbuKhousa et al., 2014; Salmon et al., 2018). Therefore, when introduced, the possible benefits of DT systems are heterogeneous and contingent on infrastructural preparedness and workforce capacity (Argyroudis et al., 2022; Lim et al., 2020). These features are especially problematic in the case of Thailand with its diversity of digitalization maturity among facilities, adding to the risk of technology fragmentation rather than unification (Ueasangkomsate, 2025; Wang et al., 2025).

Conceptually, the sociotechnical systems theory, resource-based view (RBV), and innovation diffusion theory together serve as a peer perspective on how adoption of DT can affect administrative efficiency. Sociotechnical theory focuses attention on the intersection of technical aspects, for example modeling capacity and interoperability, with social ones, such as staff capacity and organizational culture (Pasmore et al., 2019). RBV shows that strategic resources such as up to date real-time data and sophisticated modelling ability can be enduring drivers of competitive advantage when they are efficiently used by healthcare institutions (Barney, 2020). Innovation diffusion theory also posits that the adoption of DT technologies is a function of perceived usefulness, compatibility with existing practices and credibility of predictive accuracy (Rogers, 2019; Venkatesh et al., 2022). Collectively, these perceptions highlight the multi-faceted nature of DT adoption: it is not only a technical deployment but an organizational change influenced by resources, individuals, and cognition.

It is important to study DT application in health care administration for two reasons: (1) the inconsistency between existing research findings, conflicting results make it hard to draw meaningful conclusions from available literature and; (2) insufficient context-specific research has been conducted in developing countries. Although some researches suggest substantial efficiency gain obtained from DT based WF modeling, the others indicate no significant or conditional impact which are frequently conditioned by facility scale, data accessibility, and staff readiness (Jeilani & Hussein, 2025; Pasvei et al., 2025; Reddy Donitiboina et al., 2026; Rezaei et al., 2025). Moreover, few studies on prediction accuracy simultaneously considered mediating effects and moderating influences of facility size within an integrated framework. In Thailand, we observe rising administrative demands and policy priority for DT with no sound evidence on the adoption of DT as a gap and challenge. This study is well placed to present operational research with the holistic perspective which allow it to address some contradictions in the literature, as well as provide pathways for resource bound health systems.

The purpose of this study is to explore and evaluate the impacts of four factors on the time saving efficiency in healthcare administrative processes: 1) real-time data availability; 2) capability of digital twin modeling; 3) system integration, and 4) staff analytical competence in Thailand. In particular, this analysis investigates the mediating role of prediction accuracy in the digital twin systems and moderation by facility size. The study aims to contribute to the theory by untangling contradictory empirical findings in previous research and to combine insights from sociotechnical systems theory, RBV, and innovation diffusion theory. From a practical point of view, the results are likely to deliver actionable recommendations for healthcare managers and policy makers wishing to enhance operational efficiency, resource allocation, as well as speed up the dessemination in digital twin technologies. In this way the paper not only adds to international debates concerning digital shifts in administration for healthcare, but provides domestic evidence on change that is pertinent to Thailand's health system as it develops.

2. Method

2.1 Research design

E-ISSN: XXXX-XXXX, P-ISSN: XXXX-XXXX
Applied Health Administration (APPHA), Vol 1, Issue 1, January 2025, Page: 32-41
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This research was designed as a quantitative cross-sectional survey, which serves the purpose of examining relationship patterns among variables at one point in time. It is a design that is often used in healthcare technology studies, because of its efficiency and ability to gather data from large populations (Lee et al., 2022; Zhang et al., 2021; Kim & Park, 2023; Singh et al., 2021). The questionnaire measure is designed to examine not only technical aspects such as modeling ability and system integration, but also human dimension such as skills of the staff associated with being able to analyze.

2.2 Population and sample

The study sample includes the health institutions operating in Thailand which have adopted digital twin technologies or are currently making arrangements to do so. With a stratified random sampling method adopted, the study aimed to have the participation of public and private hospitals and clinics, covering several regions. The representative sample size is established in accordance with Cochran's formula for finite populations; setting the confidence level at 95% and the margin of error at 5% (Cochran, 1977; Saunders et al., 2022; Hair et al., 2021; Taherdoost, 2019).

2.3 Data collection

Data collection Data were collected using a structured self-administered questionnaire, which was distributed to administrative staff, IT personnel and workflow coordinators in the health facilities that were selected. The questionnaire consists of proven metrics of online data availability, digital twin modelling capability, integration of systems, skills of staff for analysis, accuracy of prediction, and efficiency of workflow. To ensure content validity and clarity, pre-testing and expert reviews were used (Bryman & Bell, 2021; Creswell & Creswell, 2018; Sekaran Developed this work was supported by Lource KUDAYONG et al. 498 & Bougie, 2020; Zikmund et al., 2021). Ethical data collection was maintained, with confidential and voluntary participation.

2.4 Variables and measurement

The study variables were categorized as follows: independent variables (the availability of real-time data, the capacity of digital twin modelling, the integration of the systems, the skills of staff for analysis), mediator (prediction accuracy of digital twin) and dependent variable (the efficiency of health services administrative workflow) and moderator (scale of organization). Both constructs are measured on a 5-point Likert scale developed by prior studies for reliability and content validity (Hair et al., 2021; Singh et al., 2021; Wang et al., 2023; Chen & Li, 2022).

2.5 Data analysis

The collected data were entirely analyzed by IBM SPSS Statistics 28. Descriptive statistics were used to describe demographic and response distributions. Internal consistency was assessed by Cronbach's α, and bivariate correlation analysis was used to measure the correlation between the variables. Direct effects were tested with multiple regression analysis and the PROCESS macro measured the power of prediction accuracy mediated effects. Moderating effects of facility size were examined with interaction terms in the regression models (Hayes, 2018; Pallant, 2020; Field, 2018; Tabachnick & Fidell, 2019). The analysis method is similar to previous research of digital twin adoption and the efficiency of the workflow in healthcare (Bai et al., 2023, Singh et al., 2021, Lee et al, 2022, Chen & Li, 2022).

3. Result

3.1 Descriptive statistics of respondents

The gender distribution of the 60 study participants was approximately equal, with slightly more female (53.3%) than male participants (46.7%). Most respondents were between the ages of 31–40 years old (41.7%), 21–30 (30%), reflecting that most are early or mid-career professionals. With respect to position, administrative staff represented the most common staff (41.7%), followed by IT personnel (33.3%) and workflow coordinators (25%), a varied mix of roles involved in healthcare

E-ISSN: XXXX-XXXX, P-ISSN: XXXX-XXXX
Applied Health Administration (APPHA), Vol 1, Issue 1, January 2025, Page: 32-41
https://doi.org/10.69725/appha.v1i1.267

administrative processes. As to facility type, half of the sample came from public hospitals (50%), while the rest of the sample came from private hospitals (30%) and clinics (20%), suggesting a diverse range of organizational settings. This spread will help create a full picture of workflow efficiency in a range of roles and facility sizes.

3.2 Descriptive statistics of study variables

The descriptive statistics of the study variables show overall high levels of mean score in each measure, which was between 3.98 and 4.20 on the 5-point scale. Staff analytic skills received the highest mean (4.15) followed by workflow efficiency (4.20), indicating that the respondents perceive high competence and efficiency in the management of their facilities. Real-time data availability (4.12) and real-time prediction accuracy (4.08) scored above average, indicating the existence of operative digital twin systems and effective data access. The system integration (though lower) 3.98 is also close to the higher limit which shows that there is enough interoperability in the departments. Moderate variability of standard errors (0.60–0.71) indicates consistent associations among individuals. On the whole, these findings establish a basis for subsequent correlation and regression analysis.

3.3 Correlation analysis

The correlation results demonstrate that all research variables are significantly positively correlated with one another at $p < 0.01$ level. E Time of data: The availability of real-timedata substantially positively corre- lates with workflow ($r = 0.6559$) and predictive ($r = 0.6050$) efficiencies, indicating thatthe acquisition of data is sup- portive of both predictive capabilities and administrative performance. Modeling technology capacity for digital twin is positively related to workflow efficiency ($r = 0.612$) and prediction accuracy ($r = 0.623$), demonstrating the contribution of model sophistication to improve operational outcomes. The quality of systems integration and the staff analytic ability also demonstrate moderate to strong relationships with the efficiency of workflows ($r = 0.598$ and $r = 0.604$, respectively), this means that both technical and human aspects co-influence the effectiveness of administrative procedures. Together, these correlations support the subsequent regression and mediation analyses.

3.4 Regression analysis direct effects

According to the regression analysis, all of the four predicting variables real-time data availability, digital twin modeling capacity, system integration and staff analytical skills have positive significant impacts on workflow efficiency. The strongest standardized effect is observed in real time data availability ($\beta = 0.296$, $t = 3.915$, $p < 0.001$) which demonstrates the necessity of having access to correct data on time in order to improve administrative performance. Digital twin modeling capability ($\beta = 0.273$, $t = 3.753$, $p = 0.001$), system integration ($\beta = 0.238$, $t = 3.438$, $p = 0.001$), and staff analytic skills ($\beta = 0.287$, $t = 3.900$, $p < 0.001$) all significantly increase workflow efficiency. The model as a whole accounts for 65.2% of the variance in efficiency of workflow ($R^2 = 0.652$, $F(4,55) = 25.92$, $p < 0.001$), demonstrating that not only technological but also human-related components are important predictors of efficient healthcare administrative practices.

3.5 Mediation analysis prediction accuracy

The mediation result shows the significant mediations of all the independent variables and the model fit by the prediction accuracy for workflow efficiency. The availability of real-time data has an indirect effect of 0.102 (95% CI: 0.035–0.180), which is similar as that of the digital twin modelling capacity (which has an indirect effect of 0.112, 95% CI: 0.045–0.195) suggesting that these technical capabilities contribute to improving work flow efficiency to a certain degree via an improvement in predictive performance. Also system integration (indirect effect = 0.098, 95% CI: 0.032-0.174) and staff analytical skills (indirect effect = 0.105, 95% CI: 0.036-0.189) contribute indirectly through prediction accuracy. This indicates that the mediating role of prediction accuracy is of vital importance when it comes to the influence of technical and human system resources to leverage administrative processes via digital twin systems, which in turn ultimately equates to far better predictions leading to better operations.

3.6 Moderation analysis facility scale

The moderation effect suggests that facility size substantially increases the effects of all independent variables on workflow performance. The interaction effect between relative data access times and facility scale (real-time data availability × facility scale) on performance is also significant and positive ($B = 0.142$, $t = 2.63$, $p =$

E-ISSN: XXXX-XXXX, P-ISSN: XXXX-XXXX
Applied Health Administration (APPHA), Vol 1, Issue 1, January 2025, Page: 32-41
https://doi.org/10.69725/appha.v1i1.267

0.011), indicating that the efficiency benefits of data access time are greater for larger facilities. Likewise, each of digital twin modeling champion(s) capacity × facility size (B = 0.128, t = 2.61, p = 0.012), system integration champion(s) × facility size (B = 0.115, t = 2.50, p = 0.015), and staff analytical skills × facility size (B = 0.130, t = 2.50, p = 0.014) respectively show significant positive interactions. These results suggest that the applicability of technology- vs people-centred strategies to maximise the efficiency of workflow, and hence human factors approaches, is moderated by facility size and reinforce the need for context specific implementation strategies in hospital settings taking into account the scale of the organisation.

3.7 Interaction plots

The simple slope analysis can provide further understanding about the moderating effect of facility size on the efficiency of workflow. For all predictors, except hemarthrosis, the high scale effect is greater than the low scale effect. Immediate data availability exhibits an effect growth is from 0.241 to 0.363 (Δ = 0.122, p = 0.011), digital twin model capacity is from 0.221 to 0.333 (Δ = 0.112, p = 0.012). Results regarding system integration improvement were also significant, with system integration increasing from 0.198 to 0.313 (Δ = 0.115, p = 0.015) and staff analytical skills increasing from 0.230 to 0.340 (Δ = 0.110, p = 0.014). These findings mean that facility size has a leverage effect on the positive influence of independent variables on workflow efficiency, i.e. technology competence and human resource training. This provides evidence for the importance of scale-sensitive approaches in digital deployments.

3.8 Summary of Hypothesis Testing

Summary of Hypotheses Testing Table 1 (d): Summary of hypotheses testing supports all conceptualized direct, mediation, and moderation links. Among the technological and human aspects, it is interesting to observe that real-time-data availability (β = 0.296), the capacity of digital twin modeling (β = 0.273), system integration (β = 0.238) and STAFF analytical skills (β = 0.287) have as a significant positive influence on efficiency of the workflow of work. A mediation analysis demonstrates that the prediction accuracy is an effective mediator to affect the workflow efficiency via these variables, and therefore, indicates the importance of prediction accuracy in such as a mediating role. With regard to the size of the NHs, moderating effects are indicated by the moderation statistics for all of the predictors; that is, for all predictors, the positive association is stronger for larger NHs compared to their smaller peers. To summarize, these findings validate the integrated model where the performance of workflow can be jointly explained by technology, staff capacity, predictive accuracy and scale of the organization and thus provide solid empirical basis for the conceptual model.

4. Discusion

4.1. *Real-time Data Availability and Workflow Efficiency*

The results show that instantaneous data availability has a dramatic impact on how efficiently healthcare administrative tasks can be performed. Managers have real-time information on patient flow, staffing levels and resource use; they can make decisions quickly and reduce operational bottlenecks. It is consistent with previous studies demonstrating an improvement in coordination, reduction of delays, and support for evidence-based decision-making in healthcare facilities through timely information (Bai et al., 2023; Lee et al., 2022; Zhang et al., 2021; Singh et al., 2021). Real-time information also allows for predictive planning and forward resource setting, vital in high through put or busy hospitals. Moreover, ongoing access to precise information minimizes administrative mistakes and enhances reporting accuracy, ultimately enabling better organizational performance. Indeed, in the current study, the greater degree of real-time data availability was positively correlated with the efficiency of workflow, indicating that the technological aspect has a critical role in determining operational efficiency in healthcare management. The findings highlight the necessity of real-time data collection, integration, and accessibility to improve administration.

4.2 *Digital Twin Modeling Capability as Predictor*

Modeling capacity of the digital twin was identified as an efficient intensity predictor. By building digital twins5 of administrative functions, hospitals test a range of scenarios and experiment with the impact of

E-ISSN: XXXX-XXXX, P-ISSN: XXXX-XXXX
Applied Health Administration (APPHA), Vol 1, Issue 1, January 2025, Page: 32-41
https://doi.org/10.69725/appha.v1i1.267

workflow changes all without interrupting the day-to-day functioning. This is consistent with recent analysis that artificial twins improve operational effectiveness, predict resource needs and facilitate scenario-based decision-making (Chen & Li, 2022; Wang et al., 2023; Kim & Park, 2022; Singh et al., 2021). For digital twin models, administrators have the ability to see complex workflows, test the impact of staffing changes, and optimize scheduling. Furthermore, the ability to predict based on digital twins allows proactive management and less reactive activity, as well as an increase in throughput. Here the higher the modeling capacity of a digital twin, the more efficient the workflow, thus highlighting that it is also the quality and precision of modeling tools which are important in order to extract valuable insights. These results underscore the readiness of technical infrastructure as well as knowledge of the technical staff in order to make the most out of the digital twin solutions on healthcare management.

4.3 *System Integration and Workflow Improvement*

System integration had a strong positive impact on workflow efficiency. Integrated IT systems enable sharing databases among departments, which helps to avoid redundancy, reduce errors and enhance coordination (Lee et al., 2022; Zhang et al., 2021; Bai et al., 2023; Chen & Li, 2022). Interoperable systems enable administrators to centralize patient data, monitor resource usage and workflows, which in turn, helps them run smooth operations and lowers administrative burden. The findings of this research suggest that the more developed the system integration, the smooth healthcare process was reported, thereby, technology translating to the actual healthcare management is of great importance in establishing and maintaining high quality of healthcare providing. Since integrated systems facilitate improved communication between personnel, staff time is saved on manual input of data, while operations can be monitored in real time. In general, these results further demonstrate the vital importance of IT system integration for maximizing operational efficiency and point to the importance of improving system interoperability in the strategies for managing healthcare facilities.

4.4 *Staffing and Analytical Skillfulness*

The study underscores the importance of staff competencies in utilising digital twin technologies and integrated systems for efficiency in work flows. Principals have competence of data analysis, hence able to make sense out of complex data, forms patterns and make evidences based decisions (Singh et al., 2021; Kim & Park, 2022; Wang et al., 2023; Zhang et al., 2021). Trained personnel further allow the digital twin system to predict and optimize, converting technical outputs into practical workflow enhancements. By staff analytical skills signifying a better workflow efficiency, the hand alone technology cannot solve the whole problem without skilled human resources. Thus, it is essential for training and continuing education programs in analytical methodology to ensure that the opportunities offered by digital twin and integration capabilities are fully utilised. This discovery highlights again the necessity of carrying human dimensions along with technical infrastructure while progressing into digitally enabled health care management.

4.5 *Mediation by prediction accuracy*

The prediction accuracy of digital twin systems influences the effect of independent variables on workflow efficiency. Precise predictions enable decision operators to anticipate operational difficulties, assign resources optimally, and prevent potential bottlenecks (Bai et al., 2023; Chen & Li, 2022; Kim & Park, 2022; Singh et al., 2021). The results show that the high prediction accuracy increases the positive effects of real time data availability, modeling capability, integration with system and analytical capabilities of the staff on the workflow efficiency. Our findings are in line with other studies which highlight how predictive analytics can improve decision-making and reduce uncertainty in administrative procedures. Prediction performance, when it mediates such relations, guarantees that organisational and technical infrastructure translates into a real benefit in terms of the workflow operations. This underscores the twin significance of system accuracy and analytic capacity to ensure efficient healthcare performance.

4.6. *Facility level as a moderator*

E-ISSN: XXXX-XXXX, P-ISSN: XXXX-XXXX
Applied Health Administration (APPHA), Vol 1, Issue 1, January 2025, Page: 32-41
https://doi.org/10.69725/appha.v1i1.267

The relationship between study variables and workload is moderated by facility size. Big healthcare facilities often possess intricate processes and rely on mature data systems, as well as digital twin models, as well as need experienced staff to manage performance effectively (Lee et al., 2022; Zhang et al., 2021; Wang et al., 2023; Bai et al., 2023). On the other hand, smaller installations might be cost-effective with simpler systems as they require less operational complexity. Premises size also moderates the value of real-time data availability, modeling capacity, system integration, and staff analytical skills. These results emphasize the importance of individually adapting technology introduction strategies to the size of a facility to ensure that also small facilities benefit significantly from digital twin applications. Facility size should be taken into account in digital health planning and implementation.

4.7 *Theoretical and practical implications*

The findings have several theoretical and practical implications. Conceptually, it combines concepts of sociotechnical systems theory, resource-based view, and innovation diffusion theory to illustrate how technology, human, and organizational-related variables combine to impact workflow efficiency. PRACTICAL IMPLICATIONS The results imply that healthcare managers should focus their resources on real-time data systems, digital twin modeling tools, integrated IT infrastructure and the staff training to achieve the maximum efficiency. Accuracy of prediction and facility size should be taken as a consideration when asserting planned technology interventions would be effective. Such findings inform global health organizations about the possible implementation of digital twin technology to optimize the administrative practice and quality of patient care provided (Kim & Park, 2022; Singh et al., 2021; Bai et al., 2023; Chen & Li, 2022).

5. Conclusion

This research presents a strong case for how digital twin technology can streamline healthcare administrative processes. Real-time data availability, digital twin modeling capability, system integration and personnel's analysis ability were all observed to directly and indirectly (through the mediating effect of prediction accuracy) affect the efficiency of workflow. Furthermore, the facility level also moderated these relationships, which means that the more advanced digital tools and better personnel small healthcare facilities have, less efficient it is than large healthcare facilities. Results indicate the need to combine physical infrastructure and human resources in order to obtain the best performance of the Administration. The reliability in predictions of Digital Twin systems plays an important role as a mediator for the return of investment in technology for operational gains. The study also underlines the need for implementation strategies to account for organizational attributes such as the size of the facility to optimize impact. Theoretically, the findings provide further support for the relevance of sociotechnical systems, resource-based view, and innovation diffusion for explaining the adoption and impact of digital technologies in health administration. Operationally, managers and policy makers responsible for healthcare management should consider the development of real-time data systems, strong modeling capabilities, interoperable IT platforms and training of staff to boost their analytical capacities. Together these will enhance workflow efficiency, encourage evidence-based choice and support patient care and organizational performance.

Availability of data

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request. The raw data is not publicly available due to institutional regulations, and confidentiality constraints with contributing hospitals.

Author contributions

Mary Phudit Thai; conceived the study, designed the research framework and drafted the manuscript. Data were collected, analysed and interpreted by Aung Shere Ruksat. The results were reviewed by both authors and the final version of the manuscript was agreed upon.

Generative AI use

E-ISSN: XXXX-XXXX, P-ISSN: XXXX-XXXX
Applied Health Administration (APPHA), Vol 1, Issue 1, January 2025, Page: 32-41
https://doi.org/10.69725/appha.v1i1.267

The only generative AI being used was to help out with the language and cleaning up the grammar. The authors also affirm that the study design, data analysis, and interpretation were performed independently by the authors without assistance of AI.

Conflict of interest statement

Conflict of interest The authors do not have any conflict of interest about this publication.

Acknowledgements

This research was supported by Naresuan University and Mahidol University. We would like to thank the collaborating healthcare facilities and staff, who made a significant contribution to data collection.

Appendix A. Supplementary data

Table 1. Distribution of healthcare facilities among samples

Facility Type	Number of Facilities	Sample Size
Public Hospitals	50	30
Private Hospitals	30	18
Clinics	20	12
Total	100	60

Appendix B. Supplementary data

Table 2. Variable Measurement

Variable	Measurement Scale	Source
Real-time Data Availability	5-point Likert scale	Smith et al., 2023
Digital Twin Modeling Capacity	5-point Likert scale	Jones & Lee, 2022
System Integration	5-point Likert scale	Wang et al., 2021
Staff Analytical Skills	5-point Likert scale	Zhang & Liu, 2020
Prediction Accuracy	5-point Likert scale	Kim & Park, 2022
Workflow Efficiency	5-point Likert scale	Lee et al., 2023

Table 3. demographic characteristics of respondents

Demographic Variable	Category	Frequency (n)	Percentage (%)
Gender	Male	28	46.7
	Female	32	53.3
Age (years)	21–30	18	30
	31–40	25	41.7
	41–50	12	20
	>50	5	8.3
Position	Administrative Staff	25	41.7
	IT Personnel	20	33.3
	Workflow Coordinator	15	25
Facility Type	Public Hospital	30	50
	Private Hospital	18	30
	Clinic	12	20

Table 4. Descriptive statistics of variables

Variable	N	Mean	SD	Min	Max
Real-time Data Availability	60	4.12	0.65	2.8	5
Digital Twin Modeling Capacity	60	4.05	0.71	2.5	5

E-ISSN: XXXX-XXXX, P-ISSN: XXXX-XXXX
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https://doi.org/10.69725/appha.v1i1.267

Variable	N	Mean	SD	Min	Max
System Integration	60	3.98	0.68	2.4	5
Staff Analytical Skills	60	4.15	0.62	3	5
Prediction Accuracy	60	4.08	0.66	2.7	5
Workflow Efficiency	60	4.2	0.6	3	5

Table 5 Pearson Correlation Matrix

Variable	1	2	3	4	5	6
Real-time Data Availability	1					
Digital Twin Modeling	0.612**	1				
System Integration	0.578**	0.641**	1			
Staff Analytical Skills	0.533**	0.502**	0.487**	1		
Prediction Accuracy	0.605**	0.623**	0.597**	0.511**	1	
Workflow Efficiency	0.655**	0.612**	0.598**	0.604**	0.672**	1

Table 6 Multiple Regression Direct Effects on Workflow Efficiency

Predictor	B	SE B	β	t	p
Real-time Data Availability	0.321	0.082	0.296	3.915	0
Digital Twin Modeling Capacity	0.289	0.077	0.273	3.753	0.001
System Integration	0.251	0.073	0.238	3.438	0.001
Staff Analytical Skills	0.312	0.08	0.287	3.9	0
$R^2 = 0.652$, $F(4,55) = 25.92$, $p < 0.001$					

Table 7 mediation analysis indirect effects via prediction accuracy

Independent Variable	Indirect Effect	SE	95% CI
Real-time Data Availability	0.102	0.038	0.035–0.180
Digital Twin Modeling Capacity	0.112	0.041	0.045–0.195
System Integration	0.098	0.036	0.032–0.174
Staff Analytical Skills	0.105	0.039	0.036–0.189

Table 8: Moderation analysis interaction effects

Predictor × Moderator	B	SE B	t	p
Real-time Data × Facility Scale	0.142	0.054	2.63	0.011
Digital Twin × Facility Scale	0.128	0.049	2.61	0.012
System Integration × Facility	0.115	0.046	2.5	0.015
Staff Skills × Facility Scale	0.13	0.052	2.5	0.014

Table 9: Simple Slopes Analysis for Facility Scale

Predictor	Low Scale B	High Scale B	Difference	p
Real-time Data Availability	0.241	0.363	0.122	0.011
Digital Twin Modeling Capacity	0.221	0.333	0.112	0.012
System Integration	0.198	0.313	0.115	0.015
Staff Analytical Skills	0.23	0.34	0.11	0.014

Table 10 Hypothesis Testing Summary

Relationship	Indirect Effect	β	t	p	Result
Real-time Data → Workflow Efficiency	0.321	0.296	3.915	0	Supported
Digital Twin Modeling → Workflow Efficiency	0.289	0.273	3.753	0.001	Supported
System Integration → Workflow Efficiency	0.251	0.238	3.438	0.001	Supported
Staff Analytical Skills → Workflow Efficiency	0.312	0.287	3.9	0	Supported
Real-time Data → Prediction Accuracy	0.305	0.301	4.102	0	Supported
Prediction Accuracy → Workflow Efficiency	0.276	0.268	3.815	0	Supported

E-ISSN: XXXX-XXXX, P-ISSN: XXXX-XXXX
Applied Health Administration (APPHA), Vol 1, Issue 1, January 2025, Page: 32-41
https://doi.org/10.69725/appha.v1i1.267

Relationship	Indirect Effect	β	t	p	Result
Facility Scale moderates Real-time Data → Workflow	0.142	–	2.63	0.011	Supported
Facility Scale moderates Digital Twin Modeling → Workflow	0.128	–	2.61	0.012	Supported
Facility Scale moderates System Integration → Workflow	0.115	–	2.5	0.015	Supported
Facility Scale moderates Staff Skills → Workflow	0.13	–	2.5	0.014	Supported
Prediction Accuracy mediates Real-time Data → Workflow	0.102	–	–	0.001	Supported
Prediction Accuracy mediates Digital Twin → Workflow	0.112	–	–	0.001	Supported
Prediction Accuracy mediates System Integration → Workflow	0.098	–	–	0.002	Supported
Prediction Accuracy mediates Staff Skills → Workflow	0.105	–	–	0.001	Supported
Prediction Accuracy mediates combined effects X1–X4 → Workflow	0.425	–	–	0	Supported

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