



Digital Twin-Enabled Decision Support for Flexible Dormitory Governance in Higher Education

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Abstract. This paper presents a digital twin-enabled decision support framework for flexible dormitory governance in higher education. The framework links student-state perception, room-resource visibility, rule-based screening, preference evaluation, and counselor review in one auditable governance loop. A pilot in Dormitory Building 9 at Panzhihua University uses de-identified data from 576 students in a 10-floor, 542-room building with a capacity of 2168 students. Compared with the manual process, the framework cuts room-allocation time from 210 to 12 min and room-reassignment time from 135 to 6 min, raises mean satisfaction from 3.0 to 4.0, reduces counselor workload from 120 to 25 h per semester, and lowers vacancy rate from 8.5% to 2.1%. The findings indicate that digital twin technology can support interpretable dormitory governance under institutional constraints.

Keywords: digital twin; dormitory governance; higher education management; decision support; service optimization

1 Introduction

As higher education institutions pursue refined governance and student-centered services, dormitory management has become a recurring scenario where efficiency, compliance, and responsiveness must be balanced. Room allocation, reassignment, late-return follow-up, and well-being support affect student experience, counselor workload, bed utilization, and perceived fairness. Yet traditional workflows often suffer from fragmented information, delayed room-state updates, repeated verification, and weak traceability. Digital twin theory provides a sound basis for integrating resources, student states, decision rules, and feedback into one closed-loop governance process^[1]. Related enabling technologies further support this transition from data visibility to operational decision support^[2].

Existing studies mainly focus on campus digital twin platforms and spatial visualization^{[3][4]}, or BIM-based facility operation^[5]. In higher education, digital twins have also been extended to learner modeling and data-driven educational support^{[6][7]}. Recent work further explores AI-based student twins^[8]. However, governance-oriented decision support for dormitory execution remains understudied. Most prior work

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emphasizes either infrastructure representation or educational prediction, but does not directly connect student twin states, room resources, hard institutional constraints, interpretable ranking, and human approval into an executable student-affairs management workflow.

This study contributes a five-layer governance architecture, a twin-based state model with rule-constrained scheme generation, a multi-criteria review mechanism, and pilot evidence of gains in efficiency, service quality, and resource utilization.

2 Related Work and Research Gap

Prior work can be grouped into three streams: campus digital twin infrastructure and facility operation^{[3][5]}; educational digital twins and learner modeling^{[6][8]}; and learning analytics or early-warning systems^{[9][10]}. Related dropout-prediction research provides an adjacent reference^[11]. Although these streams provide useful technical foundations, they do not directly address room-level dormitory governance, which must simultaneously consider room feasibility, student compatibility, institutional rules, and accountable approval. Table 1 positions this study against these streams and clarifies the governance gap addressed here.

Table 1. Positioning of this study against representative related work.

Type	Representative focus	Management limitation
Campus DT	platform, space, facility operation	limited support for room-level governance execution
Education DT	learner model and educational analytics	limited coupling with dormitory policies and rules
Risk analytics	prediction, warning, intervention	prediction-oriented rather than governance-oriented
This study	dormitory governance decision support	closed-loop pilot validation under actual rules

The research gap is therefore not a lack of digital data itself, but the absence of an operational bridge from data to dormitory governance decisions. The target problem in this paper is to continuously update student twin states from multi-source records, generate feasible room schemes under hard constraints, rank the feasible set with interpretable management indicators, and retain counselor review as the final accountability mechanism.

3 Governance Framework and Decision Methodology

3.1 Governance Architecture and Twin-Based State Representation

The proposed framework contains five interconnected layers: physical entities, data connection, virtual models, decision services, and feedback. Physical entities include students, rooms, access-control devices, and dormitory business nodes. The data layer standardizes and integrates access, smart-card, student-affairs, questionnaire, and

review records. The twin layer maintains synchronized student and room states. The decision layer performs rule checking, candidate generation, and recommendation ranking. The feedback layer records counselor review, manual correction, and post-execution outcomes. Viewed from a management perspective, this architecture transforms fragmented dormitory information into a shared decision basis for student-affairs governance. Figure 1 shows the end-to-end architecture.

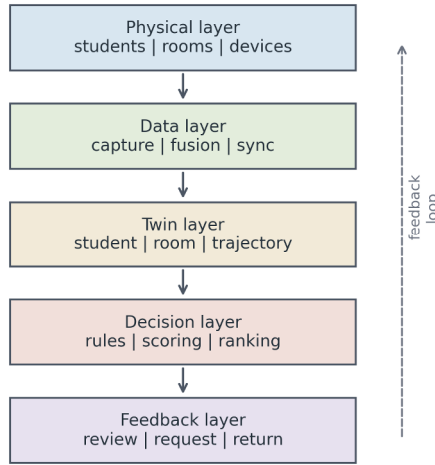


Fig. 1. Architecture of the digital twin-enabled dormitory governance framework.

For management implementation, the student twin is represented as a compact state vector that jointly captures relatively stable attributes and time-varying observations:

$$z_i(t) = [p_i, b_i(t), q_i(t), e_i(t)] \tag{1}$$

$$z_i(t + 1) = \lambda z_i(t) + (1 - \lambda)\varphi(u_i(t), m_i(t)) \tag{2}$$

where p_i denotes static profile attributes such as grade, major, and gender; $b_i(t)$ denotes behavioral observations from access and consumption records; $q_i(t)$ denotes questionnaire-derived preference descriptors; $e_i(t)$ denotes event tags such as reassignment requests or warning states; $u_i(t)$ represents newly captured data; $m_i(t)$ denotes management events; and λ controls the balance between historical state retention and event-driven refresh.

This formulation highlights that the twin is not a static data repository. Rather, it is a reusable governance state unit that supports multiple management triggers with consistent semantics across allocation, reassignment, alerting, and service response.

3.2 Rule-Constrained Scheme Generation

Dormitory governance decisions first require a feasible-set construction step. Let Ω_i denote the initial candidate-room set for student s_i . Hard constraints, including gender zoning, bed capacity, room status, safety regulations, and special health requirements,

are encoded as binary predicates and applied before any flexible evaluation is attempted:

$$\Omega_i^f = \{r_j \in \Omega_i \mid \prod_{h=1} c_h(s_i, r_j) = 1\} \tag{3}$$

This step guarantees policy compliance and compresses the decision space before ranking, thereby reducing repetitive verification and unproductive counselor review.

3.3 Multi-Criteria Evaluation and Review Mechanism

After infeasible rooms are removed, the remaining candidate set is evaluated by nine flexible indicators covering roommate compatibility, learning-life coordination, resource fit, and risk control. Weights are initialized by fuzzy analytic hierarchy process and then updated modestly through operational feedback so that the system remains interpretable while adapting to repeated correction patterns. This mechanism allows governance decisions to remain both evidence-based and traceable, which is especially important in student-affairs management. Figure 2 shows the corresponding workflow of rule-constrained scheme generation and multi-criteria evaluation.

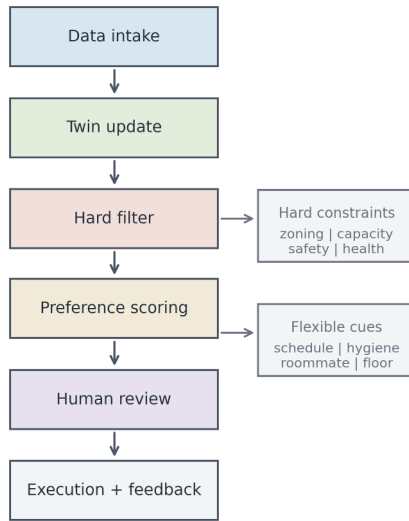


Fig. 2. Rule-constrained scheme generation and multi-criteria evaluation workflow.

$$\text{Score}(s_i, r_j) = \sum_{k=1} w_k f_k(s_i, r_j), \sum_{k=1} w_k = 1 \tag{4}$$

$$r_i^* = \underset{r_j \in \Omega_i^f}{\text{argmax}} \text{Score}(s_i, r_j) \tag{5}$$

$$w_k^{t+1} = \alpha w_k^t + (1 - \alpha) \widehat{w}_k^t \tag{6}$$

$$T(N, M, d) = O(NM + NMd) = O(NMd) \tag{7}$$

Table 2. Flexible indicator groups and managerial semantics.

Group	Indicators	Managerial value	Evidence source
Preference fit	schedule, hygiene, roommate expectation	enhance roommate compatibility	survey + history
Life-study coordination	major affinity, regional affinity	reduce friction and communication cost	student records
Resource fit	floor fit, bed balance, special-needs fit	enhance utilization and suitability	room state + application
Risk control	conflict avoidance	lower repeated adjustment probability	conflict log

With fixed, low indicator dimension d , complexity is dominated by candidate enumeration and scoring. Table 2 summarizes the indicator groups. The method therefore supports near-real-time management at building scale while preserving interpretable score decomposition for review.

3.4 Workflow Embedding in Student Affairs Management

The prototype uses a lightweight service pattern linking data ingestion, identity mapping, twin updating, rule evaluation, ranking, and review interaction. Access-control, smart-card, and student-affairs records are standardized into a unified identity space before state refresh. When allocation, reassignment, late return, or well-being events occur, task-specific rules call the same twin service instead of isolated silos. This design reduces duplicate state maintenance, improves traceability, and suits existing counselor workflows. Table 3 maps the main tasks to triggers, outputs, and manager actions.

Table 3. Mapping between management tasks and system support functions.

Task	Trigger	System output	Manager action
Room allocation	new intake + room state	ranked feasible room schemes	counselor review
Room reassignment	conflict, vacancy, urgency	target-room recommendation	manual approval
Late return	access anomaly + routine deviation	risk level and reminder	follow-up interview
Well-being support	warning tag + activity trace	supportive service suggestion	case review

This paper evaluates allocation and reassignment only; late-return alerting and well-being support are retained as extensible scenarios. The scope matches available records and keeps the paper framed as a management-application study.

4 Case Study and Management Effectiveness

4.1 Case Context and Data Sources

The case study was conducted in Dormitory Building 9 of Panzhihua University, a 10-floor building with 542 rooms and a capacity of 2168 students. A pilot area covering

576 students, including 328 freshmen and 248 senior students, was selected because data completeness and operational control were stronger at the prototype stage. The dataset includes de-identified access-control and smart-card records, student-affairs records, freshman preference questionnaires, and autumn-semester psychological screening data. This setting is typical of dormitory governance scenarios with clear policy boundaries and high coordination pressure.

4.2 Evaluation Design and Indicators

The study uses a descriptive workflow comparison rather than a randomized experiment. The baseline is the existing manual workflow, and the assessed indicators are response time, mean satisfaction, counselor workload, repeated reassignment requests, and vacancy rate. These indicators reflect process efficiency, service quality, and resource utilization.

Because the available business records do not preserve sufficiently detailed grouping information or complete response-count records for public disclosure, quantitative reporting is intentionally limited to room allocation and room reassignment. The system is further restricted to governance support rather than automatic disciplinary action, and all recommendations require counselor review before execution. This boundary is necessary both for data governance and for responsible deployment in the campus context.

4.3 Operational Results

Table 4 summarizes the quantitative outcomes in the pilot area. Relative to the manual workflow, the proposed framework delivered substantial reductions in processing time, manual workload, repeated adjustment requests, and vacancy rate, while also improving student-perceived matching quality. Figure 3 offers a visual comparison of the efficiency and outcome differences between manual and system-assisted workflows. Taken together, these results indicate that the framework produces measurable managerial benefits rather than only technical automation gains.

Room-allocation speed improved by a factor of 17.5 and room-reassignment speed by 22.5. These gains are operationally meaningful because the framework shifts repetitive work from counselor-side checking to feasible-set construction and ranked recommendation generation. The decline in repeated requests and vacancy rate further indicates better initial matching quality.

Table 4. Core managerial performance results in the pilot area.

Metric	Manual	System	Relative gain
Allocation time	210 min	12 min	94.3% reduction
Room reassignment time	135 min	6 min	95.6% reduction
Overall satisfaction	3.0	4.0	+33.3%
Counselor workload	120 h	25 h	79.2% reduction
Repeated requests	45	12	73.3% reduction
Vacancy rate	8.5%	2.1%	75.3% reduction

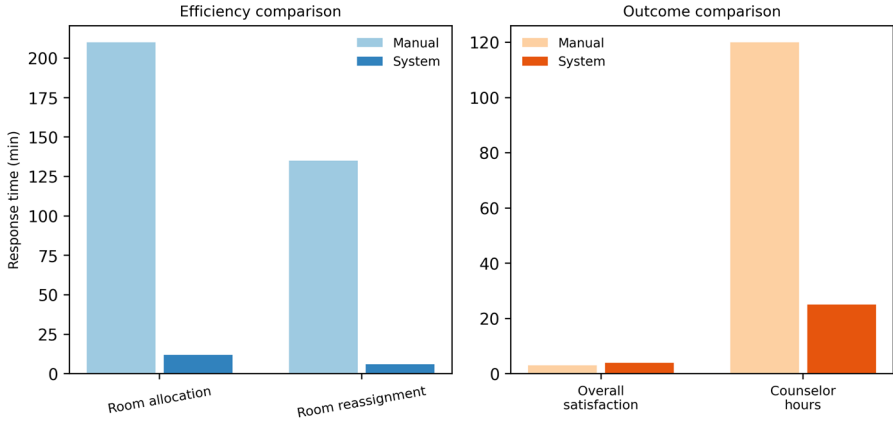


Fig. 3. Efficiency and outcome comparison between manual and system-assisted workflows.

4.4 Management Implications and Limitations

The current findings should be interpreted as deployment-oriented management evidence rather than broad statistical inference. The pilot demonstrates that a digital twin-enabled dormitory framework can operate stably in a real administrative setting with incomplete yet manageable data, but it does not by itself establish universal superiority over all possible allocation algorithms or governance arrangements.

Even with these constraints, the framework remains transferable because student states, room resources, hard constraints, and ranking indicators are parameterized and modular. Local adaptation is therefore concentrated mainly in rule parameters, data interfaces, and counselor review policies rather than in the core twin model. For management practice, this means the framework can serve as an enhancement layer for existing student-affairs governance rather than as a disruptive substitute for institutional procedures. Table 5 summarizes the main limitations of the present study and the corresponding mitigation measures.

Table 5. Main limitations and current mitigation.

Issue	Current mitigation	Residual limitation
Pilot-only scope	claims limited to the pilot area	generalizability still limited
Manual baseline	focus remains on operational improvement	no direct algorithmic benchmark
Incomplete records	descriptive reporting only	no statistical test
Sensitive data use	de-identification and human review	full public release not possible

A practical next step is phased expansion from the pilot area to the whole building and then to multiple buildings, supported by longer observation windows, clearer reporting of return counts and adoption rates, and comparison with heuristic or integer-programming baselines.

5 Conclusion

This paper presents a digital twin-enabled decision support framework for flexible dormitory governance in higher education. By integrating state representation, rule-constrained scheme generation, multi-criteria evaluation, and counselor-in-the-loop review, the framework converts fragmented dormitory records into an executable governance mechanism. The pilot in Dormitory Building 9 shows that the approach can improve decision efficiency, service quality, and resource utilization while preserving institutional compliance and human accountability. Future work should strengthen the empirical base through multi-building deployment, longer observation, and comparison with alternative governance or optimization baselines.

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