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EDUCATIONAL INSTITUTIONS AS URBAN MICROSTRUCTURES: AI-BASED SPATIOTEMPORAL OCCUPANCY ANALYSIS AS A DECISION SUPPORT LAYER FOR ACADEMIC MANAGEMENT

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1. Introduction

Urban intelligence has shifted from macro-infrastructure optimization toward the governance of institutional microstructures — such as campuses — that operate as the city's functional fabric [1]. While these environments are ideal for smart sensing and data-driven decision-making, academic management remains largely reactive, relying on delayed, aggregated reports that provide little insight into the actual behavior of students in space and time [2, 3]. This gap is not merely technical. The absence of real-time spatial insight prevents institutions from distinguishing between stochastic absences and sustained behavioral disengagement — a distinction that, if made early, could enable timely and targeted pedagogical intervention. To address this, we argue that spatiotemporal occupancy analysis, powered by privacy-preserving computer vision, integrated with existing educational information systems, functions as an actionable decision-support layer for academic management. By treating occupancy data as a behavioral proxy, the system detects early behavioral signals associated with student disengagement. This approach advances spatial analysis as a meaningful dimension of learning analytics, enhancing the governance of educational quality.

2. Occupancy as a behavioral proxy

Traditional attendance systems capture a binary: present or absent. They offer no information about when within a class session students leave, how density evolves over the course of a semester, or whether absences cluster around specific disciplines, instructors, or time slots. This granularity is precisely what spatiotemporal occupancy analysis provides. Computer vision techniques enable the continuous estimation of human occupancy over time [4] without requiring individual identification. When aggregated into time series, these spatiotemporal data reveal occupancy curves: patterns of presence evolution that serve as predictive indicators rather than mere descriptions. A consistent decline in room occupancy (*e.g.*, during the second half of evening classes or week-over-week reductions in specific disciplines) constitutes a signal that precedes institutional consequences. By detecting these behavioral precursors long before they appear in formal records, the system allows for proactive management. Furthermore, the framework adopts a privacy-by-design approach by operating exclusively on quantitative occupancy counts, with no biometric processing or individual identification of any kind. This design strictly adheres to the data minimization principles of the Brazilian General Data Protection Law (LGPD) [5], avoiding the legal and ethical complexity of personal data governance. By processing only the number of individuals present in a space, the system ensures privacy as a foundational feature, enabling large-scale institutional deployment with minimal compliance burden.

3. A framework for integration: occupancy as a decision support layer

The value of occupancy data multiplies when treated not in isolation, but as one layer within a broader institutional data ecosystem. We propose an occupancy-integrated decision support layer, positioned between raw sensor output and academic governance, structured around three integration axes: (a) Occupancy × Enrollment: cross-referencing physical presence against enrollment records surfaces attendance discrepancies that formal systems fail to capture; (b) Occupancy × Discipline Metadata: disaggregating data by subject, instructor, and time slot enables the identification of recurrent disengagement patterns with statistical confidence; and (c) Occupancy × Academic Performance: correlating occupancy time series with grade records determines the point at which declining presence becomes predictive of failure, enabling calibrated and timely intervention. An artificial intelligence layer (AIL) operationalizes these axes as an anomaly detection and alert engine. Trained on historical

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data, it learns baseline occupancy patterns and flags meaningful deviations, generating structured alerts such as: *"Discipline X, Tuesdays at 19h, has shown a 37% occupancy drop over three weeks"*. The AIL's output is not a decision, but a structured input to human judgment. Coordinators retain full interpretive authority, and the system is designed to support evidence-based decisions with sufficient lead-time for effective response. To formalize this mechanism, we propose the Occupancy Discrepancy Index (ODI) as the primary trigger for institutional intervention, defined as $ODI = \frac{(E - O_a)}{E}$, where E represents total enrollment, and O_a is the average occupancy detected during the class period. For instance, an alert could be triggered when $ODI > 0.3$ for two consecutive sessions, a threshold calibrated to distinguish sustained behavioral disengagement from stochastic variation such as occasional adverse weather or traffic disruptions. As illustrated in Fig. 1, this framework enables real-time monitoring through spatiotemporal heat maps, shifting academic management from intuition to evidence and supporting pedagogical interventions while remediation is still possible.

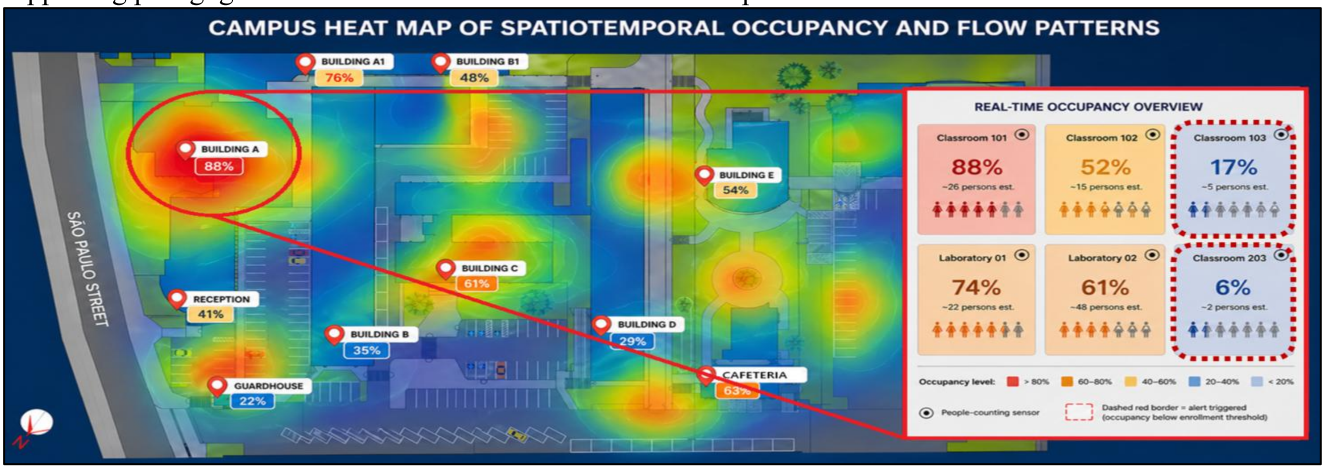

Fig. 1. *Spatiotemporal occupancy heat map with detailed building-level analytics. Color intensity represents human density, from high (red) to low (blue). The dashboard on the right provides a granular view of Building A; dashed red borders (Classrooms 103 and 203) illustrate automatic alerts triggered when observed occupancy (17% and 6%, respectively) diverges significantly from the enrolled headcount. Such discrepancies serve as leading indicators for pedagogical intervention. Icons denote the positioning of non-identifiable people-counting sensors across the monitored infrastructure.*

4. Conclusion and strategic implications

The proposed framework positions educational institutions as intelligent urban microstructures, where AI-driven spatial analysis transforms raw occupancy data into actionable governance intelligence. By detecting sustained disengagement before it surfaces in formal records, the AIL enables coordinators to act on evidence rather than intuition, addressing root causes while remediation remains viable. Beyond the pedagogical dimension, aggregated occupancy intelligence could support infrastructure planning, adaptive energy management, and campus flow optimization, aligning academic environments with the smart city paradigm. Ultimately, this is a governance proposition: treating spatial behavior as a legitimate, actionable dimension of educational quality.

5. References

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