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Dynamic Building Activities Management in Healthcare Facilities: A Simulation Study in a Catheterization Lab

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ABSTRACT
We present a simulation-powered dynamic building activities management system, intended to help coordinate distributed decision-making activities in sensor-equipped complex buildings, such as healthcare facilities. It provides overall "awareness" of the current state of the facility and analyzes the impact of simulated alternative future actions of each actor in every space, simultaneously. These analytics are evaluated according to Key Performance Indicators (KPI), resulting in a recommendation for enacting the most desirable outcome. A preliminary simulation study based on St. Bernardine Medical Center (SBMC) Cardiac Catheterization Lab (CCL) is presented.

Author Keywords
Smart Environments; Human Behavior Simulation; Space Utilization; Hospital Environments; Activity Management.

ACM Classification Keywords
I.6.3 SIMULATION AND MODELING: Applications;
I.6.5 SIMULATION AND MODELING: Model Development; J.6 COMPUTER-AIDED ENGINEERING.

1 INTRODUCTION
Buildings have been traditionally considered as passive containers where the activities of their occupants take place. They are, to a large degree, unaware of the people who inhabit them, and the activities they are involved in. The occupants too are, to a large extent, unaware of the activities occurring in other parts of the building. Such limited reciprocal awareness between spaces, people, and activities hampers the ability of complex organizations, such as healthcare facilities, to avoid enacting activities that may conflict with one another and wisely allocate resources such as personnel, equipment and spaces, leading to inefficient space utilization and staff and patient dissatisfaction.

Recent developments in ubiquitous computing and IT systems fostered the introduction of sensing technologies into the very fabric of built environments [1,11]. Temperature, humidity, illuminance, CO_2, occupancy, and noise sensors have been coupled with Building Management Systems (BMS) for demand-based control strategies of mechanical and electrical services to improve occupant comfort and energy efficiency [9,10]. Wearable devices have been deployed to monitor people's physiological conditions and provide feedback to care providers [2]. Ambient sensing technologies (e.g., cameras, depth, thermal, radio, and acoustic sensors) detect the presence and activities of people and have been used especially in healthcare facilities for patients' movement management, elderlies' fall detection, gait analysis, and mental wellbeing symptoms screening [7].

These methods, however, only provide local awareness of a specific human activity without capturing holistic human behavior patterns unfolding in the entire building. Besides, they provide reactive responses to a detected phenomenon, without informing the holistic management of building operations and space utilization in response to – and anticipation of – emerging needs.

To address these shortcomings, prior work of the authors conceptualized a framework for a simulation-powered Building Management System capable of sensing the presence and location of humans and building assets using an independently developed Visible Light Communication (VLC) system [14], simulating what-if scenarios, and choosing alternative user activities and building operations that will maximize specific Key Performance Indicators (KPIs) [8].

This approach marks a departure from existing approaches for modeling and simulating human-building interactions:

- Instead of replicating the mere physical conditions of real-world assets – as it is done in current Digital Twin applications [15] – our approach supports the joint and interdependent modeling of spaces, people, and activities for predictive analytics of alternative operational strategies.
- Different from existing human behavior simulation approaches that evaluate the impact of architectural design changes on space utilization patterns [17,18], our approach enhances the dynamic resource allocation

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process (i.e., spaces, people, equipment) within existing building fabrics.

- Rather than relying on video game engines to represent detailed human-building interactions [20,21], our model operates on a more abstract representation of spaces, people and operations to enable real-time simulation of complex what-if scenarios for workflow decision making.
- While Operations Research approaches model healthcare workflows to investigate operational (in)efficiencies in a facility using queuing models [19], Business Process Modeling (BPM) [12] and Petri Nets [3,4] we advocate a more nuanced, holistic and comprehensive approach that integrates multiple modeling techniques of spatial (physical), operational (medical), and social (people) aspects, to improve the overall effectiveness of healthcare facilities and allow them to better address everyday needs.

The benefits of this approach have been previously discussed in a hypothetical application involving the allocation of spaces to host an emergency procedure performed in a generic catheterization lab [8].

In this study, we build upon and significantly extend prior work by proposing a novel building activities management system that accounts for the detailed decision-making of each actor and thus enables prediction and analysis of the implications of multidimensional resource allocation strategies (i.e., people, spaces and equipment) on spatial, social and operational KPIs.

We demonstrate this approach in a simulation study at the Catheterization Lab at St. Bernardine Medical Center. Since the VLC system responsible for sensing human behavior patterns is not yet deployed in the space, the following study evaluates the efficacy of the proposed system once it will be fielded.

2 BUILDING ACTIVITIES MANAGEMENT

The proposed system is comprised of three components: (a) A digital **model** of the building ecosystem that includes spaces, actors, and activities, informed by data collected using field studies as well as occupancy and activities sensors when installed in the built environment; (b) A **simulation** engine that generates alternative future occupancies and activities scenarios; and (c) An **analysis** and evaluation method for quantifying the implications of the simulated futures on spatial, social, and operational KPIs defined in collaboration with stakeholders. We detail below the key components of the proposed simulation model.

Space Model. It represents the built environment where activities take place. The environment is abstracted into a graph where *Nodes* represent inhabitable spaces such as rooms, corridors, and open spaces, and *Links* indicate how spaces can be traversed. Nodes store *static* information, such as a space function (e.g., operating room, waiting area, corridor), as well as *dynamic* information, such as the identity of the occupants currently located within those spaces and the activities they are engaged in. A *room manager* is responsible for coordinating the behavior of actors inside each room. For example, the room manager of a Cath Lab verifies the presence of all required participants to perform a surgery and, if all conditions are satisfied, it coordinates the procedure execution.

Actor Model. It represents the building occupants. Each actor stores *static* information about their roles (e.g. nurses, doctors and patient) and group members (e.g. a doctor is associated with specific nurses and patients to treat), as well as *dynamic* information about their location and status (e.g. a patient status indicates if he/she is pre- or post-procedure).

Activity Model. It represents the dynamic interactions between actors and spaces, such as people's movement across spaces or domain-specific behaviors such as a catheterization procedure, which involves multiple participants. Each activity has an associated duration, a list of people that take part in it, and one or more spaces where it can take place.

Narrative Model. It represents the goal-oriented behaviors of actors engaged in structured sequences of individual or collaborative activities [16]. For example, a catheterization procedure narrative involves the following activities: preparing the patient, preparing the room, moving the patient to a specific lab where the procedure takes place, executing the procedure, directing the patient to a recovery area and finally discharging the patient. Each narrative is responsible for determining the next destination of one or more actors and then yielding control of the actors to a specific room manager that directs their local behaviors. Upon successful completion of an activity, the room manager yields back control to the narrative, which identifies the next destination for the actor.

Narrative Management System. It coordinates the unfolding of multiple narratives and it resolves conflicts when multiple narratives require the same resources (i.e. spaces, people or equipment). For example, if two narratives direct a patient to a holding area, but only one bed is available, the room manager responsible for the holding area reports a conflict to the narrative manager, which explores, via simulation, the implications of alternative conflict resolution strategies, and it recommends the one that best balances selected KPIs of spatial, social and operational performance.

In this study, the Python language has been used for modeling the system components, simulating their behavior over time, and generating a set of tables in support of analytics. The intent is to develop a system that can return decision support to occupants at interactive rates.

3 A STUDY AT ST. BERNARDINE MEDICAL CENTER

This case study aims at demonstrating the efficacy of the proposed building activities management system to predict and analyze the overlapping implications of spatial,

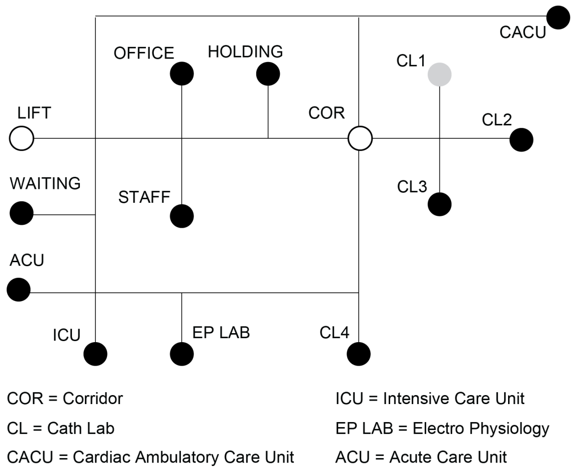


Figure 1. Graph representation of CCL

operational, and staffing aspects in the Cardiac Catheterization Lab (CCL) at St. Bernardine Medical Center (SBMC).

SBMC is a 342-bed not-for-profit health care facility. Its Inland Empire Heart & Vascular Institute is one of the largest heart programs in Southern California [5]. Some of the services it provides include cardiac catheterization labs, diagnostic services, cardiothoracic surgery, inpatient care, outpatient cardiac rehabilitation and emergency services. The CCL serves outpatients (OP), inpatients (IP) for diagnostic and interventional procedures as well as emergency cases to treat, for example, ST-segment elevation myocardial infarction (STEMI).

The CCL is a complex and dynamic environment, replete with staffing, operational, and spatial challenges. At any given time, decisions must be made concerning the allocation of resources (spaces, people, activities) to maximize operational efficiency, space utilization, and staff and patient satisfaction. Actions are taken simultaneously by multiple actors located in different spaces, who are typically not aware of the actions and needs of other actors.

4 DATA COLLECTION AND MODELING

Existing performance conditions of the CCL were studied in a preliminary 3-day site visit conducted in February 2020. The study included tracking, self-reporting by the Cath lab, data from surveys/interviews, and observational data. That study was used as the basis for constructing the system's knowledge base, space configuration, operational workflow, and staff/patient profiles.

4.1 Spaces

Figure 1 depicts an abstract layout of the CCL, where each space is replaced by a node and the connections between spaces are indicated by arcs. The space is comprised of five labs: three Cardiac Catheterization labs (CL), one Electro Physiology (EP) lab, and one Hybrid Cath Lab (CL4). CL1-3 form one cluster, while CL4 and EP lab form a separate cluster. CL1 was under renovation at the time of the visit, so

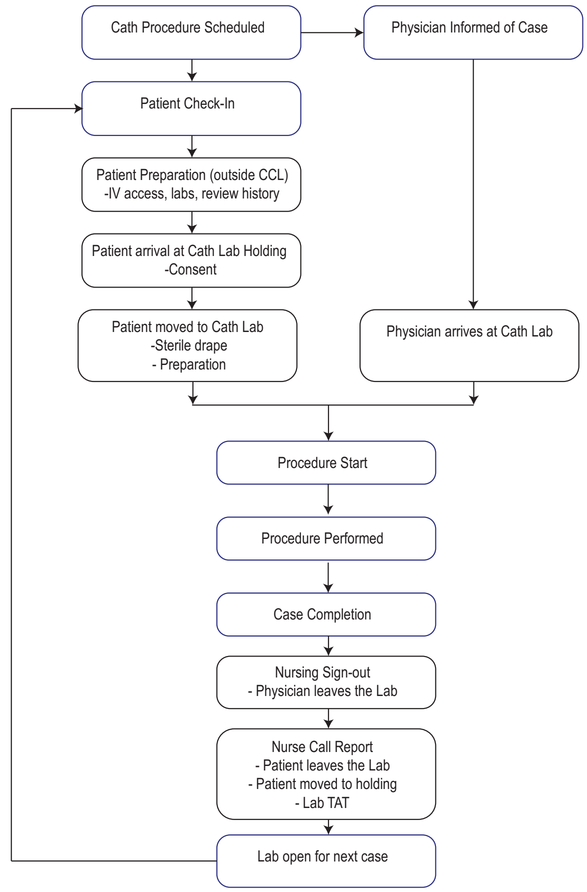


Figure 2. Typical CCL workflow for the planned procedures

it has not been considered in this study. The holding area at the CCL has 3 beds for the pre- and post-procedure preparation and recovery of patients.

The CCL interacts with a Cardiac Ambulatory Care Unit (CACU), a 16-bed unit for outpatients coming into the department for treatment, where patients are prepared for the procedure and recover post-procedure. At SBMC, the CACU is located on a different level of the hospital. Other interacting units include the inpatient ward (IP) for the inpatients, ICU for the patients from the Intensive Care Unit, the Emergency Department (ED) for emergency cases, and the Acute Care Unit (ACU) for the outpatient surgery patients. The ACU is a 12-bed unit where the patients are prepped for the procedures, and they recover at the Post-Anaesthesia Care Unit (PACU) post-procedure. The waiting room for families of the patients undergoing a procedure at the CCL is located outside the CCL, and has a capacity of 20 persons.

4.2 Actors

The CCL is staffed by 16 cardiologists, 20 Registered Nurses, 8 X-Ray Technicians, a manager, coordinator, scheduler, and 3-4 specialists on call. Patient transfers are carried out by the registered nurses or x-ray technicians. There are no assigned persons for the transfers and the staff

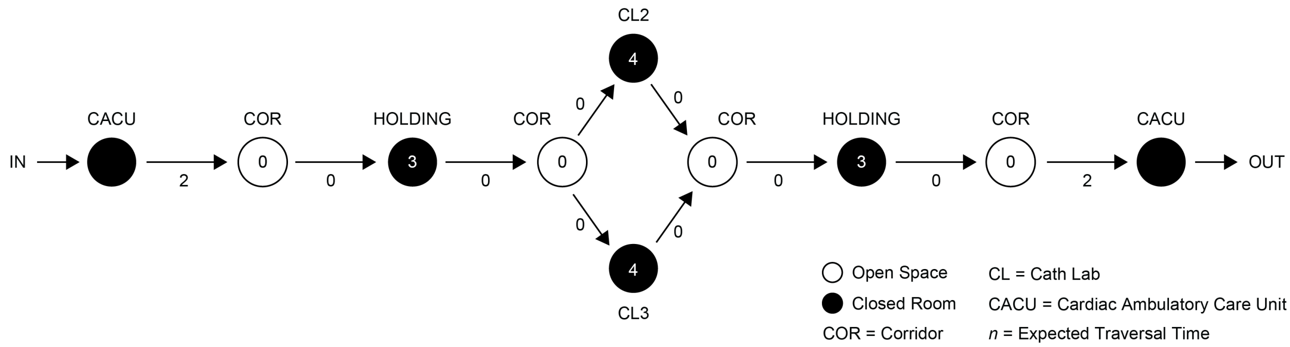


Figure 3. Graph representation of CCL workflow for a planned narrative

	Scenario	**Positive** outcomes (+)	**Negative** outcomes (-)
A	N1+P1 move to COR N5+P2 stay in CL3 TAT begins in CL2	P2 is protected in CL3 TAT in CL2 is not delayed	P1 is exposed in COR TAT in CL3 is delayed, delaying next procedures scheduled for CL3
B	N5+P2 move to COR N1+P1 stay in CL2 TAT begins in CL3	P1 is protected in CL2 TAT in CL3 is not delayed	P2 is exposed in COR TAT in CL2 is delayed, delaying next procedures scheduled for CL2
C	N1+P1 move to COR N5+P2 move to COR TAT begins in CL2 + CL3	TAT in CL2 is not delayed TAT in CL3 is not delayed	P1 + P2 are exposed in COR Congestion in COR
D	N1+P1 stay in CL N5+P2 stay in CL	P1 is protected in CL2 P2 is protected in CL3 No spatial congestion in COR	TAT in CL1 is delayed, delaying the next procedure TAT in CL2 is delayed, delaying the next procedure

Table 1. Expected implications of alternative decision-making strategies (N= Nurse, P= Patient, CL= Cath Lab, COR = Corridor)

takes turns to conduct either the patient transfer or handle the turnaround time (TAT) of the lab between procedures. Patient transfers are governed by a protocol that specifies the number and type of staff involved. It allows for an outpatient without a monitor to be transferred by an x-ray technician. A registered nurse is required for the transfer of patients with monitors and the transfer of patients from units such as the IP, ICU and ACU. The protocol may require two persons for transfers, at least one of whom must be a registered nurse.

4.3 Activities and Narratives

The CCL uses a block scheduling system, wherein a specific room on a specific day is assigned to a cardiologist or cardiologist group. A typical diagnostic procedure involves a medical team comprised of a cardiologist, two registered nurses and one x-ray technician, while an interventional procedure also includes an additional registered nurse and an anaesthetist. The duration of the procedures depends on the type of procedure and the patient's condition. There are 1-2 registered nurses in the holding room to observe patients.

Figure 2 shows the typical workflow of the CCL operations. The pre-procedure preparation starts in the holding room and includes checking of the procedure order, IV placement, blood tests and lab tests as needed, after which the patient is ready to be transferred to the CL for the procedure. The times depend on the type of patient and type of procedure. There can be additional waiting time depending on the availability of the cardiologist for the procedure, including other causes for delays such as transfer times, availability of room and staff for the procedures, or Turn Around Time (TAT), which is the time between adjacent scheduled cases when one patient leaves the procedure room until the time the next patient enters the same room. A TAT will typically include cleaning of the room post procedure, and preparation of the room for the next procedure. It is carried out by a registered nurse and an x-ray technician.

For the purposes of the simulation, the workflow has been abstracted into a graph representation (Figure 3). Only two CLs are simulated. Numbers inside the nodes show the expected duration of an operation, in abstracted time units. Numbers on the arcs show the traversal time between nodes. We use abstracted time units, instead of actual minutes. 0 time units indicate traversal time within the CCL, where spaces are sufficiently close to each other to make traversal time insignificant. Transfer to-from the CACU is significant, therefore the indicated time units are higher.

Patients typically spend 2 hours in pre-procedure preparation and wait at the CACU, up to 2 hours at the CCL, followed by a recovery of 2-3 hours or 6 hours depending on the procedure and complications.

5 SIMULATION SCENARIO

In this study, we simulate the activities of five patients, three of whom are post-procedure and two pre-procedure; two doctors; five nurses; and two x-ray technicians. Only two Cath Labs are simulated. Both happen to complete their respective procedures at the same time, namely – two post-procedure patients need to be moved to the holding room for recovery.

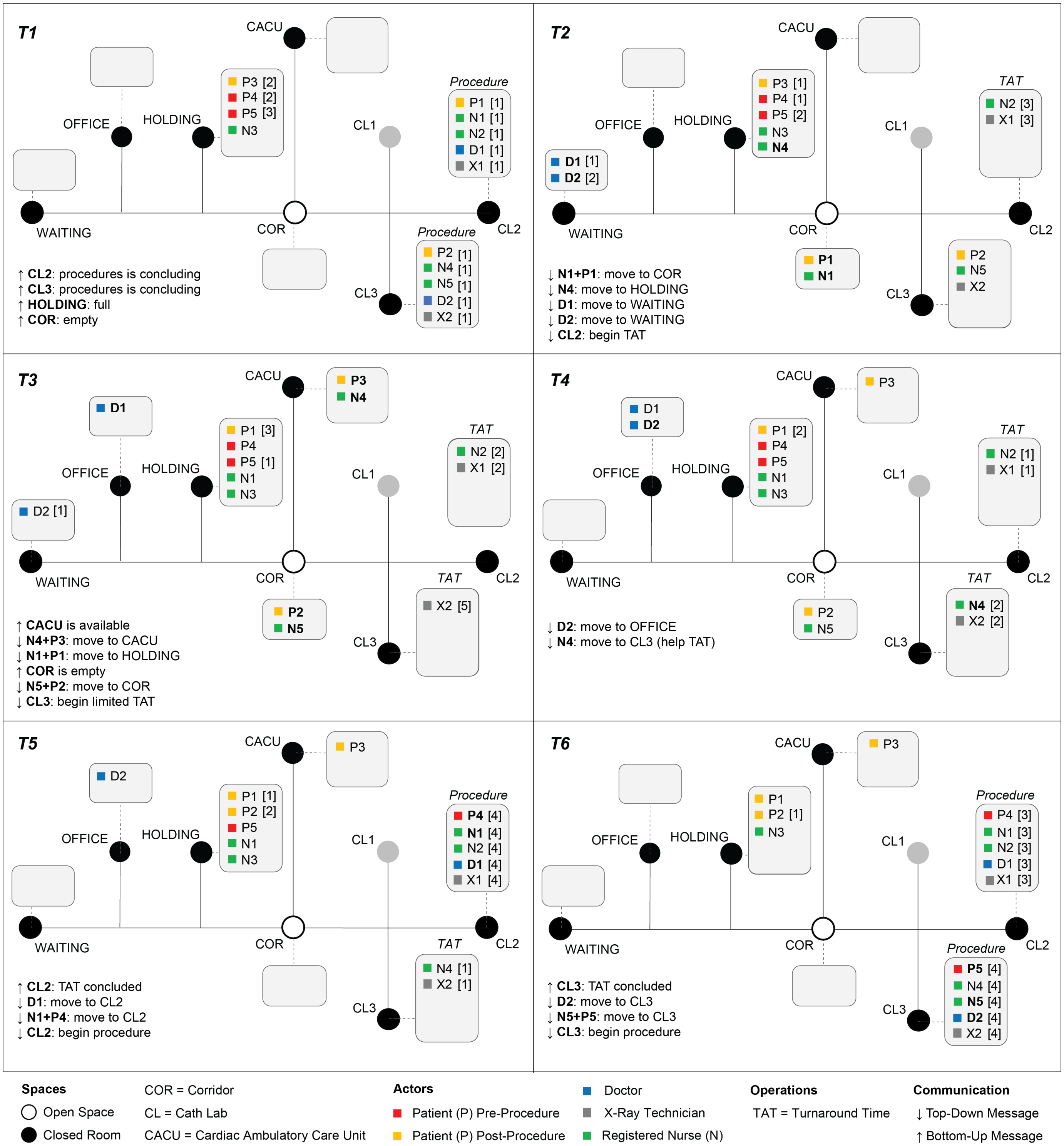


Figure 4. Simulation snapshots at different time steps (T*n*)

The holding room is full, with two pre-procedure patients and one post-procedure patient (Figure 4 - T1). This is the overall situation, as detected by the Building Management System. The staff must choose between four possible actions: (a) Move post-procedure patient P1 to the corridor (COR), awaiting a free space at the Holding room; (b) Move post-procedure patient P2 to the corridor (COR), awaiting a free space at the Holding room; (c) Move both post-procedure patients (P1 and P2) to the corridor, awaiting a free space at the Holding room; or (d) Keep both post-procedure patients in their respective CLs, awaiting a free space at the Holding room. Since all patients must be accompanied by a registered nurse at all times, moving any of them to the corridor also means that one nurse must move to the corridor, or stay with the patient in the CL. Each option has expected advantages and disadvantages, illustrated in Table 1.

To help the staff choose the action that will lead to the most beneficial outcome, the consequences of each option are simulated and analyzed. The sequence of steps for option A is depicted in Figure 4 (T2-6).

6 ANALYSIS

Analysis of the simulation results includes actors' satisfaction, space utilization, and operational efficiency (Figure 5):

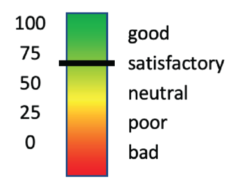
Actors' Satisfaction. In this study, we consider only patients' satisfaction. Their degree of satisfaction is based on the following assumptions: (a) Patients are most satisfied when they undergo some procedure; (b) Patients are less satisfied when waiting; (c) Patients are not satisfied when they must stay in the corridor.

Space Utilization. Space utilization is measured as a percentage of time a space has been used for the activity for which it was designed: (a) If use = designed, then the score is 100; (b) If use ≠ designed, then the score is < 100. Scores are summed up and divided by the number of spaces to obtain the average space utilization score.

Operational Efficiency. The duration of activities as experienced by patients were tracked and compared to the expected (benchmark) durations (in time units) depicted in Figure 4. Activities are measured as a percentage of BENCHMARK/ACTUAL time each patient spends in each space: (a) If ACTUAL = BENCHMARK then the score is 100%; (b) If ACTUAL > BENCHMARK then the score is less than 100%; (c) If ACTUAL < BENCHMARK then the score is 100% (no bonus is given for completing an activity earlier than its benchmark).

Actors' Satisfaction

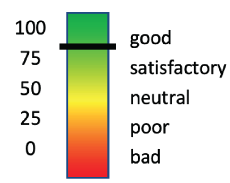
TIME	P1		P2		P3		P4		P5	
1	CL2_proc	100	CL3_proc	100	HOLDING	75	HOLDING	75	HOLDING	75
2	COR_wait	0	CL3_wait	50	HOLDING	75	HOLDING	75	HOLDING	75
3	COR_wait	0	CL3_wait	50	HOLDING	75	HOLDING	75	HOLDING	75
4	HOLDING	75	COR_wait	0	CACU	75	HOLDING	25	HOLDING	75
5	HOLDING	75	COR_wait	0	CACU	75	HOLDING	25	HOLDING	25
6	HOLDING	75	HOLDING	75	CACU	75	CL2_proc	100	HOLDING	25
7	HOLDING	75	HOLDING	75	CACU	75	CL2_proc	100	CL3_proc	100
8	HOLDING	75	HOLDING	75	CACU	75	CL2_proc	100	CL3_proc	100
		59		**53**		**75**		**72**		**69**



Average: 65.63%

Space Utilization

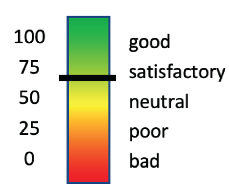
TIME	CL2		CL3		COR		HOLDING	
1	procedure	100	procedure	100	empty	100	full	75
2	TAT	100	wait	25	full	0	full	75
3	TAT	100	wait	25	full	0	full	75
4	TAT	100	TAT	75	full	0	full	75
5	TAT	100	TAT	100	full	0	full	75
6	procedure	100	TAT	100	empty	100	full	75
7	procedure	100	procedure	100	empty	100	available	100
8	procedure	100	procedure	100	empty	100	available	100
		100		**78**		**50**		**81**



Average: 77.34%

Operational Efficiency

	P1		P2		P3		P4		P5	
	Act.	Ben.	Act.	Ben.	Act.	Ben.	Act.	Ben.	Act.	Ben.
CACU										
COR										
HOLDING							5	3	3	3
COR							0	0	0	0
CL2	4	4								
CL3			6	4						
COR	2	0	2	0						
HOLDING	5	3	3	3	3	3				
COR					0	0				
CACU										
	11	7	**11**	7	**3**	3	**5**	3	**3**	3



Average: 69.70%

Figure 5. Analysis of spatial, social and operational implications of a decision-making strategy (Act. = Actual duration, Ben = Benchmark)

	A	B	C	D
Actors	66	66	59	60
Spaces	77	77	77	73
Operations	70	70	51	64
	70.8	**70.8**	**62.4**	**66.9**

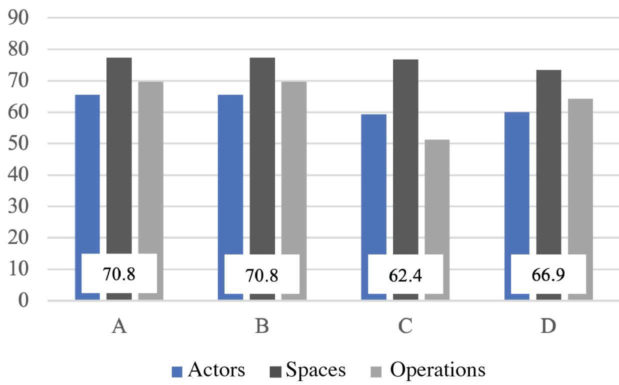


Figure 6. Comparative evaluation of alternative decision-making strategies

These analyses are being performed for each one of the alternative scenarios discussed in Table 1, and their relative merits/drawbacks can be compared and evaluated (Figure 6).

The comparative evaluation shows that options A and B, where one of the patients is moved to the corridor while the other stays in the Cath Lab, are preferable to either moving both patients to the corridor (option C) or leaving both in their respective Cath Labs (option D). Options A and B allow TAT to proceed in one of the labs, thus mitigating the delay of subsequent procedures scheduled for that lab, while inconveniencing only one of the two patients. Option C will allow TAT to commence in both labs, but will inconvenience both patients and crowd the corridor. Option D will delay TAT in both labs.

7 CONCLUSIONS AND DISCUSSION

Typically, healthcare workflow studies address operational aspects while ignoring the other aspects like occupancy, location and activities of users and equipment. Instead, the proposed approach considers the mutual interactions and dependencies of three different points of view: (a) Spatial, (b) Operational, and (c) Social. *Spatial* impact includes situations that arise due to spatial design and layout such as the configuration of the different spaces and distances between them, including the activities in each space. *Operational* issues describe each occupant's current, past and future activities, including the schedule of planned procedures and protocols in the case of disruptions. *Social* issues describe the role of every person in the system and their responsibilities, abilities and well-being.

We contend that these points of view, while unique, are not independent of each other: they affect, and are affected by one another. For example, the limited space in the holding room necessitates parking patients in the corridor, which causes congestion, occupies precious staff time, and inconveniences the patients. While one component might be more dominant than another, it is not separable from others. Therefore, solutions for the identified problem must address all these components together, or at least examine each potential change for its effects on all three aspects of the facility. Improving one aspect may negatively impact another. Alternatively, improving one aspect may also improve others. We call this "the power of seeing the whole," or the ability to see and understand aspects of the situation that is not visible from one point of view alone.

The case study illustrated in this paper aims at demonstrating how simulation can be used to effectively predict and analyze the mutual interdependence of spatial, social, and operational factors over time thus augmenting the decision-making abilities of building occupants to account for "the power of the whole". Simulation-powered operations management could mark a departure from existing approaches that are heavily based on human intuition. It will account more closely for the implications that operational decisions may have on space utilization patterns and evaluate tradeoffs between alternative operational strategies to identify the solution that best balances the outcomes for the involved stakeholders, including patients, visitors, and staff members. Intelligent and adaptive environments capable of continuous operational awareness and data-driven actionable recommendations hold promise to help the overall healthcare delivery system adapt faster and better to rapidly changing spatial, operational, and staffing needs.

More broadly, the proposed approach can provide a method to reduce the gap between the expected performance of a facility and its actual use using quick decision-making cycles that do not require long and expensive architectural design renovations. This can lead to dynamic and more efficient resource allocation in response to or anticipation of unfolding events. For example, spaces could be dynamically repurposed and allocated to alleviate congestion building up in waiting areas; staff members could be rerouted to prevent operational bottlenecks in a different part of the buildings; and equipment could be prepositioned in anticipation of future demand. This ability enables an overall, comprehensive point of view into the present, past, and also future of some situations not visible from the individual actor's point of view. It is what air traffic controllers use to direct airplanes without risking mid-air collisions [6], and GPS-based systems like Waze [https://www.waze.com] use to help drivers choose the fastest route to their destination to avoid traffic jams. Similarly, a building management system could efficiently and flexibly direct assets (people, spaces, and equipment) to where they are needed at any given time.

Equipping buildings with spatial, social, and operational awareness is expected to have a major impact on the way buildings are conceived: the design of dynamic environments will require architects to collaborate with buildings' stakeholders as well as experts from other disciplines (e.g., Operations Research, Artificial Intelligence, Social Sciences, Environmental Psychology, and Electrical Engineering) to coordinate the responses of a 'living' machine [13]. In this way, they will be able to design integrated human experiences in which the human, digital and the physical are interwoven to achieve the best match between operational efficiency and people experience.

Future work will aim at integrating established simulation frameworks such as Petri Nets [3,4] and Discrete Event Simulation (DEVS) [22] in an effort to scale up the system. Future studies will also identify improvement opportunities, set goals based on the organizational needs, identify the relevant KPIs and define how to measure them. This will be followed by a stepwise implementation of the changes and a systematic plan to evaluate solutions. Effective stakeholder engagement from varied organizational levels on the plan and roadmap for initiatives and interventions will ensure securing buy-in and support from the key decision makers and the entire CCL team.

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