SYMPOSIUM ON SIMULATION IN ARCHITECTURE + URBAN DESIGN
SimAUD 2020

Simulation-Powered Smart Buildings Management enabled by Visible Light Communication

Yehuda E. Kalay [1,2], Haripriya Sathyanarayanan [1], Davide Schaumann [3], Albert Wang [4], Gang Chen [4] and Ramdas G. Pai [4]

[1] University of California Berkeley, US
{kalay, haripriya_snarayanan}@berkeley.edu

[2] Technion, Israel Institute of Technology
Haifa, Israel
kalay@technion.ac.il

[3] Jacobs Technion-Cornell Institute
New York, US
davide.schaumann@cornell.edu

[4] University of California
Riverside, US
{aw, gachen}@ece.ucr.edu
ramdas.pai@medsch.ucr.edu

ABSTRACT

Throughout history, buildings have been considered passive containers in which occupants' activities take place. New sensing technologies enable buildings to detect people presence and behavior. At present, this information is mostly used to trigger reactive responses, such as heating and cooling operations. We argue that truly smart environments can leverage sensed information to proactively engage with the occupants and inform decision making processes with respect to which activities to execute, by whom and where. Such ability will transform buildings from passive to active partners in the daily lives of their inhabitants. It stems from the omniscience of sensor-equipped buildings that will "know" all that is happening everywhere within (and around) them at any given moment and can predict, through simulation, the expected consequences of alternative operational decisions. Such ability is mostly relevant for hospitals and other complex buildings, where actions taken in one part of the building may affect activities in other parts of the building. We are developing a simulation-powered building management system that resolves space, actor and activity-based conflicts while harnessing data collected via visible light communication. We demonstrate this approach in a case study in the catheterization lab of a major hospital.

Author Keywords

Smart Environments; Human Behavior Simulation; Space Utilization; Hospital Environments; Visible Light Communication.

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

Sensing technologies that enable buildings to detect people's presence have been in use for the past few decades, mostly to trigger reactive responses to people's presence (e.g., heating/ventilating, lighting, security, etc.). We argue that truly smart environments can leverage sensed information about the locations and activities of their inhabitants to proactively engage with the occupants and inform their decision-making processes with respect to which activities to execute, by whom and where (in addition to autonomously activating building resources).

To help assess the potential impact of "smart" buildings on their occupants, we are developing a simulation-powered building management system that can sense the location and activities of human and building assets, extrapolate patterns of utilization, simulate what-if scenarios and suggest future user activities and resource allocation to maximize specific Key Performance Indicators (KPIs). Different from existing approaches, our system is able to evaluate the implications of potential conflict resolution strategies using a multi-agent simulation system that accounts for individual and collaborative activities.

While the approach being developed is agnostic of the sensing and communication technology used, we have chosen Visible Light Communication (VLC) technology, which is embedded in a building's LED lighting system [10].

VLC has been chosen because unlike radio frequency it is highly localized, and it does not interfere with the building's other sensitive instruments, which is critical in the case of hospitals (our chosen case study). In addition, because it is embedded in the building's LED lighting system, it requires little additional infrastructure compared to other technologies.

Information derived from the VLC system is combined with models of actors' activity schedules, profiles, and space affordances to understand what happens in each space at any

SimAUD 2020 May 25-27, Online

given time. This data on the building's current state of the occupancy and utilization is used to simulate alternative possible future actions for each actor and to resolve possible conflicts that may occur. The simulation and decision-making process are driven by a previously developed narrative-based modeling system to simulate human behavior in buildings [12,13]. It produces alternative future states, revealing the consequences of enacting different resource allocation strategies. A priority function is used to evaluate and compare the alternative futures and choose the one that maximizes a utility function. Once the decision is made, the system uses VLC to communicate the information to the relevant actors who can enact them. We demonstrate our approach by applying it to the Catheterization Lab in a hospital.

It is our contention that smart environments of this kind hold promise to enhance the decision-making capabilities of buildings and their inhabitants, thus enable building management strategies that support human needs and efficiency requirements, especially in mission-critical facilities, such as hospitals.

2 ADAPTIVE BUILDINGS

We have identified three levels of building automation that help us understand and assess the potential impact of adaptive buildings on their occupants, namely buildings that can change their performance dynamically in response to the changing environmental conditions and the needs of their inhabitants [5].

Feedback regulated adaptability is based on the concept of *feedback loop*, where the output of a machine is linked to its input and compared against some desired performance measures. Departure from the desired condition triggers adjustments in the performance of the machine, hence its output. The ubiquitous thermostat demonstrates this principle: as the HVAC system heats (or cools) the air inside a building, the thermostat monitors the air's temperature. When that temperature reaches the thermostat's set point (the desired temperature), it sends an electrical signal to the HVAC plant, shutting it off. When the air cools below the set point (or, conversely, heats up beyond it), the thermostat sends a signal which turns the HVAC plant on, and so on.

Enabling the building to sense and respond to changing needs is a relatively simple reactive kind of automation, which has been implemented in areas of control, regulation and supervision of electrical, mechanical and climatic control equipment.

Adding a *functional model* to networked building systems and appliances allows for a proactive adaptability approach to automation, which we call **model-based adaptability**. It helps to regulate the environment in *expectation* of events, rather than in response to them. A functional model of a building is one where the occupants' behavior patterns are programmed in advance, based on learning their typical preferences, so the building can anticipate and position itself to support recurring events, not only to respond to them.

Model-based adaptability has been demonstrated by the University of Colorado's ACHE (Adaptive Control of Home Environments) project [9]. Using the model, the house could anticipate the inhabitants' preferences and adjust the operation of devices, accordingly, freeing them from the chores of manually controlling of their environment.

Total-environmental adaptability will be reached when the building not only responds—reactively or proactively—to its inhabitants' behavior, but will actively engage, even manage them. Such active management requires much more information than the locations of the inhabitants and prevailing environmental conditions: it must include information about spatial conditions, activities, and the inhabitants themselves.

Such information comprises of three components: (1) *Space* information, which includes the configuration of the building (rooms and the connections between them), the intended purpose of each room (e.g., a hospital patient room, a nurse station, etc.), the environmental conditions prevailing in each space (light, temperature, noise, etc.), and current location of each inhabitant. (2) *Activities* information, which includes each inhabitant current, past and future activities. It also includes information about customary scheduled activity sequences, and what to do in case of unexpected activities (e.g., 'Code Blue' in a hospital). (3) *Inhabitants'* (which we call 'actors') information, which includes the identity of each actor, his/her profile (role in the organization—doctor, nurse, patient, visitor, etc.), abilities, degree of fatigue, and more.

Once the building management system has access to all this information, it can form an image of the current state of the whole building and its inhabitants. Using simulation, it can predict alternative future states, which can be evaluated according to some Key Performance Indicators (KPI), so that the most suitable future state can be chosen.

3 OVERVIEW OF THE PROPOSED APPROACH: THE POWER OF SEEING THE WHOLE

We call this ability "the power of seeing the whole." It is what air traffic controllers use to manage planes in the air, and GPS-based systems like Waze use to help drivers choose the fastest route to their destination.

The ability to see the whole provides an overview of some situation, not visible from the individual actor's point of view. Much like an air traffic controller can direct airplanes without risking midair collisions, a building management system could direct assets (people, equipment) to where they are needed at any given time, alert security personnel in case of disturbances, and more. Furthermore, as evident from Figure 1, this ability extends from the present to the past: it is possible to trace previous locations of individuals and equipment at prior points in time.

It is our contention that this ability can also be extended into the future by way of simulation, which will allow the building management system to predict the future locations and activities of the inhabitants. It could, therefore, consider alternative "futures" and help choose the one most desired (according to some predefined criteria).

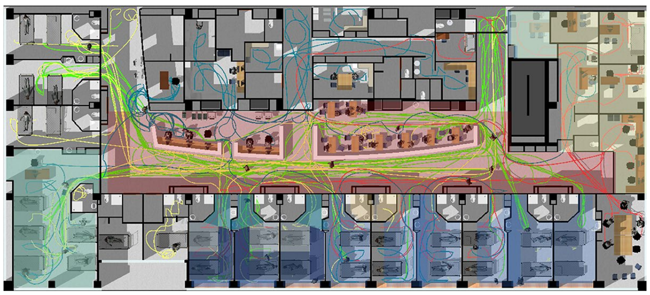

Figure 1. Locating and tracking people in a hospital ward.

4 METHOD

We propose a simulation-powered Building Management System aimed at Total Environmental Adaptability that leverages the power of "seeing the whole." It will sense the presence and location of humans and building assets, extrapolate patterns of behavior and utilization, simulate what-if scenarios and suggest modifications to user activities and building operations to maximize specific KPIs. The system is composed of three main components: (1) sensing, (2) decision-making, and (3) acting.

4.1 Sensing

A building can "sense" various aspect of the environment, including the presence of people, through a variety of embedded sensors. If the data collected by each sensor is to be made available to the building as a whole, these sensors must be networked. While wireless connectivity is preferred, in hospitals—which are the domain and case study for our research—sensors based on radio-frequency (RF) wireless technologies have many major limitations, such as interference with medical devices that may potentially put patient safety at risk [1], and compliance with extremely high security and regulatory standards to ensure patient privacy, which cannot be ensured because RF signals are publicly open, and their security is only guarded by certain encryption methods.

An alternative to RF is communication based on visible light. Traditional incandescent and fluorescent lamps are being replaced by energy-efficient solid-state LEDs [7]. Other than being more energy efficient, LEDs can be switched ON/OFF at a speed of tens of MHz without flickering visible to the eye, enabling Visible Light Communication (VLC) at high data rate by modulating LED light [3]. Wireless VLC has many advantages over traditional RF technology: (a) the optical spectrum is unlicensed, unrestricted and orders of magnitude wider (300THz) than the crowded RF spectrum, making wireless streaming of big data possible for large number of users; (b) it allows more emission power for higher data rates and better quality of service (QoS) without risking human health; (c) unable to penetrate walls, it ensures high security and privacy; (d) being interference-free, it can co-exist with RF technologies; (e) VLC devices are cheaper than RF components.

Ubiquitous VLC wireless systems will consist of modulated LEDs (lamps) for broadcasting and user terminals (smartphones with embedded photodetector as transceivers) to realize full-duplex optical wireless streaming anywhere, anytime for anyone. In a sense, VLC wireless is "free" because it is built on existing LED lighting infrastructure, providing VLC wireless streaming at beyond-Gbps speeds. LED also allows visible light real-time communication and positioning, making it possible to share data, locate personnel and equipment instantly and securely.

4.2 Decision making

The system combines the sensed data with other data, to help make decisions about future actions. Since these decisions involve human activities, which are dynamic and depend on many factors such as spatial, occupational, and personal conditions, the method chosen to help depict future situations is *simulation*.

Simulation approaches have been used to analyze the dynamic relationship between human activities and the surrounding environments in both existing and not-yet-built environments. In particular, recent work on narrative-based modeling [12,13] demonstrated a viable method to simulating day-to-day occupancy scenarios in complex facilities, like hospitals. The approach is centered on *narratives*, which are rule-based scripts that coordinate the collaborative behaviors of heterogeneous actors (e.g., doctors, nurses, patients) who perform a structured sequence of activities (e.g., checking a patient) that unfold in semantically rich spaces (patient rooms, clinics, etc.). Different from other simulation approaches that mostly focus on linear, straightforward pedestrian movement or evacuation scenarios, the narrative-based model uses a combination of a top-down coordination mechanism to enforces the performing of structured sets of tasks, while allowing for bottom-up adaptations to dynamic social and spatial conditions, such as the emergence of unplanned narratives (staff-visitors interactions) that can potentially delay planned narratives (checking a patient).

Our narrative-based decision-making system consists of three components: (a) a library of spaces, actors, activities and narratives that represent the spaces that people inhabit, the actors that populate the spaces, the activities they perform, and the narratives they are involved in; (b) a simulation engine that calculates the behavior of the entities over time; and (c) an evaluation module that calculates and visualizes a list of KPI so that the simulated outcomes of different future narratives can be compared to predefined KPI.

4.2.1 Library of spaces, actors, activities and narratives

- *Space* entities comprise a model of the building, typically generated using CAD or BIM tools, including both physical (walls, floors, doors, furniture, etc.) and non-physical components (rooms, corridors, and open areas). Both physical and non-physical building components also store semantic information that indicate how they can be used. A 'clinic room' zone, for instance, indicates that the space can be used for clinical activities, such as treating a patient. Such zones can, for instance, record the presence and activities of the occupants within their boundaries.
- *Actor* entities include a profile (e.g., patient, nurse, companion, doctor) that determines the type of narratives the actor can be associated with, stores static information, such as the names of patients that a nurse is responsible for treating, and updates dynamic information about the current activity the actor is performing as well as other actor properties, such as tiredness.
- *Activities* represent the possible interactions that actors have with other actors or with spaces. In this work, we are concerned with abstracted activity descriptions, their spatial location, the identities of the participating actors, and their duration. In this way, we can limit the number of activities modeled and focus on their spatial/social implications in real-world clinical situations. We also model activities in a modular fashion, so they can be reused multiple times within a narrative or across narratives.
- *Narratives* are the heart of the simulation. They use the aforementioned components (spaces, actors, and activities) and combine them into scripts that direct actors' behavior by associating them with specific activities performed at a given time and space(s), while accounting for possible context-dependent adaptations to unforeseen situations.

4.2.2 Simulating

A narrative manager coordinates the unfolding narratives over time. In addition to the execution of planned narratives, the narrative manager is also responsible for triggering unplanned narratives when the necessary preconditions are satisfied (e.g., an impromptu conversation that takes place when a staff member and a visitor meet in a corridor). The simulation is powered by Unity 3D, a popular game engine.

4.2.3 Evaluating

The simulations result in measurable performance indicators, which can be compared to predefined threshold measures or relatively to one another. They may include hard and soft criteria. Hard criteria are quantitative, measurable performances, such as patients and staff walking paths and distances, patients' length of stay, overall throughput, congestion, staff or space utilization. Soft criteria are typically qualitative, based on subjective perceptions, such as social, psychological, and organizational policies.

In many cases, the same performance results may be valued differently by different stakeholders. To create a building-wide management system, it is therefore necessary to create a shared world view that incorporates the relative merits of each action from different points of view and reconciles the differences among them in light of shared, higher-level objectives [2]. A tradeoff mechanism balances competing needs. It may choose to optimize one performance characteristic over others or strike a balance in the degree to which any performance criterion is achieved, assuring that overall performance is maximized [6].

4.2.4 Implementation details

In addition to using Unity 3D as the simulation engine, which was chosen because it features advanced physics and AI libraries to model collision avoidance and pathfinding, we use Microsoft C# to represent the properties of actors, activities, narratives and for the narrative manager. Spaces have been modeled using McNeel Rhinoceros 3D software, and then imported into Unity 3D.

4.3 Acting

Once the comparative evaluations are completed, it is then possible to recommend enacting the most desired—or least disruptive—action. This action is communicated to the relevant stakeholders via the building's two-way communication system, which as mentioned earlier in our case is by means of VLC. If the preferred action involves building systems, such as HVAC, lighting, etc., the preferred action may be communicated directly to the assets involved.

Like other "recommender" systems, such as GPS-based driving instructions, the actors may accept or ignore the recommended action. Either way, their action will be sensed by the building, and become input for the next round of simulation/evacuation/action.

5 CASE STUDY

To demonstrate the proposed system, we have chosen to implement it hypothetically on a Cardiac Catheterization Laboratory (CCL). A CCL is a suite of rooms in a hospital with diagnostic imaging equipment used to visualize the arteries and the chambers of the heart and treat any stenosis or abnormality found. It performs diagnostic, interventional, and electro physiology procedures, serving outpatients, inpatients, and emergency cases. Typically, 20-25 procedures are planned for each workday. In addition, the CCL handles 1-2 unplanned emergency cases every day. The procedure rooms are staffed by 15 staff members and operate from 7.30am to 5pm every day and may run overtime depending on the procedures and other emergencies.

While the CCL is only one unit in the hospital, it impacts, and is impacted by other units. The challenge is to evaluate those impacts to avoid conflicts and maximize the utility of the overall hospital. The simulation process necessarily requires abstraction of a complex system into a simplified model and experimenting iteratively on it to test the relationship among many variables interacting in complex and often unpredictable ways [14].

The case study CCL has five Cath Labs: three Cardiac Catheterization (CC) labs, one Electro Physiology (EP), lab, and one Hybrid Cath Lab (HCL). A diagnostic procedure involves a team of three staff members (a cardiologist and two nurses) and lasts 20-30 minutes. An interventional procedure involves a six-member team (cardiologist, anesthesiologist, three nurses and a technician), along with a nurse in the observation area, and lasts 45-90 minutes. The labs interact with a 15-bed Cardiac Acute Care Unit (CACU) where patients are prepared for the procedure and recover from it.

Figure 2 depicts the typical (planned activities) workflow of the CCL operations, and includes the actors, activities, space and average duration for each activity. The case study focuses on the workflow that begins after pre-procedure preparation of the patients, either at the CACU for outpatients, the hospital nursing wards for inpatients, or the Emergency Department (ED), depending on the type of patient. The key activities include the patient transfers to and from the procedure room, patient preparation for the procedure at the procedure room and the actual procedure, along with the actors involved in the activities.

To demonstrate the proposed system, we look at the impact of an *unplanned event* on the CCL and the overall hospital. An unplanned event consists of emergency cases known as STEMI (ST-Elevation Myocardial Infarction). That is a very serious type of heart attack during which one of the heart's major arteries (one of the arteries that supplies oxygen and nutrient-rich blood to the heart muscle) is blocked. For STEMI patients, access to a facility with percutaneous coronary intervention (PCI) capabilities is time-critical: Door-to-Balloon (D2B) time must be less than 90 minutes. The STEMI may arise within the hospital, at the inpatient ward and ED, or arrive from outside the hospital. While the typical protocol for a STEMI is going to the ED first, the D2B can be reduced by pre-activating the CCL for the STEMI thereby improving patient outcomes [15].

Although the frequency of STEMI cases is typically 1-2 a day, they can be considered 'unplanned' events that disrupt planned events at the CCL. A STEMI protocol requires an immediate activation of a suitable Cath lab and medical team to prevent delays in care [8].

This presents a suite of challenges within the CCL, as it may disrupt planned schedules for patients, medical teams, and planned allotment of CLs for the different procedures. Furthermore, not all the Cath Labs are suitable to treat a STEMI. Suitable CLs might be occupied with ongoing procedures at different stages of completion, and cardiologists may be occupied or have a scheduling conflict if assigned the STEMI patient. Furthermore, these challenges go beyond the CCL, as changes to the planned schedules can have a negative effect on other outpatients and inpatients: patients that were scheduled to undergo treatment may be bumped, requiring rescheduling (of outpatients) and longer stays (for inpatients). Hence, an action that may seem optimal for the CCL may adversely affect other units of the hospital, and thus be less optimal overall.

It is the goal of the system described here to critically evaluate all the options facing the CCL in case of a STEMI, and to recommend the overall most suitable plan of action for the hospital as a whole (subject, of course, to the constraints of the STEMI protocol and others).

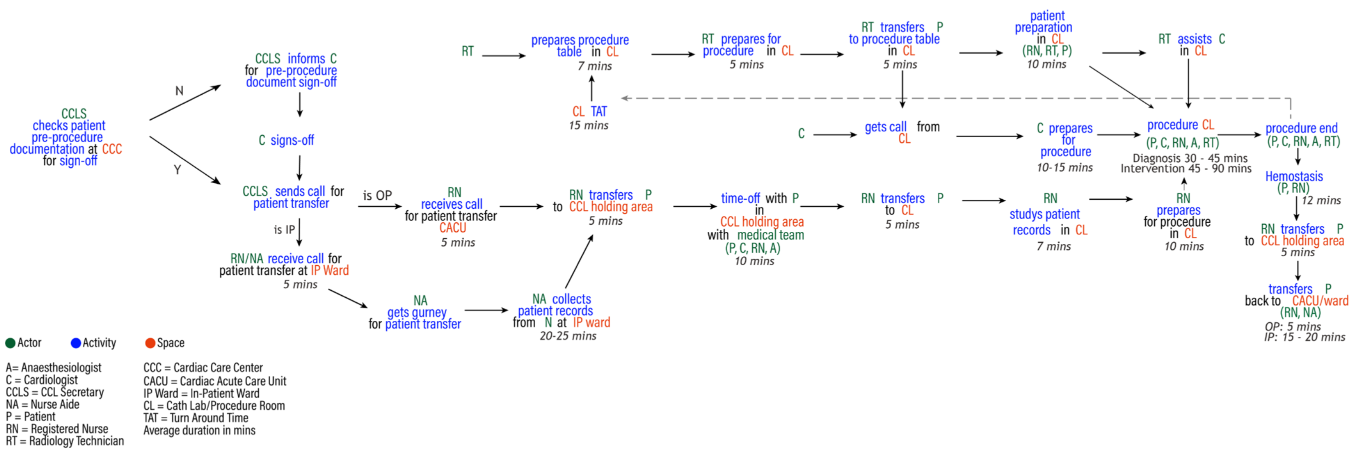

Figure 2. Typical Cath Lab workflow for the planned procedures.

5.1 Sensing

To determine the overall best course of action we must start by detecting the state of the CCL when a STEMI protocol is declared. This is done through the VLC system and associated data profiles for the spaces, actors, and activities. Table 1 shows the hypothetical state of the five Cath Labs in terms of the types of patients and medical teams involved, and the type of ongoing procedures, expected duration and possibility for interruption of the ongoing procedures by the unplanned STEMI event.

Space	Type	Procedure	Patient	Duration	Time left
CL1	CC	Intervention	IP1	80 mins	40 mins
CL2	CC	Intervention	IP2	45 mins	45 mins
CL3	CC	Diagnosis	OP1	30 mins	30 mins
CL4	HCL	Diagnosis	OP2	30 mins	10 mins
CL5	EP	EP Study	OP3	35 mins	30 mins

Table 1. Narratives of the planned procedures in the CCL.
IP = In-Patient; OP= Out-Patient; CC=Cardiac Catheterization; HCL=Hybrid Cath Lab; EP = Electro Physiology

From Table 1 it can be determined that:

- The procedure in CL1 is half-way through.
- The procedure in CL2 has not yet begun.
- The procedure in CL3 has not yet begun.
- The procedure in CL4 is 2/3 complete.
- CL5 is an EP lab, therefore it is not suitable to treat the STEMI.

5.2 Decision-Making

To determine which one of the available labs to choose for treating the STEMI (CL1, CL2, CL3, or CL4), we need to simulate the consequences of choosing each one of the labs and evaluating their relative merits.

5.2.1 Simulation

Using the Event-Based simulation described earlier, we find:

- The procedure in CL1 cannot be interrupted, therefore that lab is not available to treat the STEMI.
- If CL2 is chosen to treat the STEMI, Patient IP2 (an inpatient) who was scheduled to be treated in that lab, will be bumped. The patient will be taken back to the inpatient ward, where he will stay at least another day before he will be treated (we assume his condition allows such postponement of the treatment). Consequently, patient IP2 will not be discharged as planned, and will continue to occupy a bed in the cardiac in-patient ward.
- The continued hospitalization of IP2 will prevent admission of an incoming patient from the Emergency Department, who was scheduled to be hospitalized in the cardiac in-patient ward. Instead, she will have to stay in the ED for another 24 hours, at a great inconvenience to her and the ED staff.
- If CL3 was chosen to treat the STEMI, Patient OP1 (an outpatient) who was scheduled to be treated in that lab, will be delayed. She will be taken back to the CACU, delaying treatment of other outpatients scheduled for the day. Since the policy of the CCL is to treat all out-patients that were scheduled for the day rather than sending them back home to be treated another day, the CCL clinical staff will have to stay for a longer shift.
- If CL4 is chosen to treat the incoming STEMI, it will take 10 minutes to complete the ongoing procedure, and another 15 minutes to turn the CL around and make it ready for the incoming STEMI. This will result in 25 minutes delay in treating the STEMI.

5.2.2 Evaluation

The results of the simulations are evaluated comparatively to a list of Key Performance Indicators partially drawn from the literature [4,11] and discussed with an expert/lead-cardiologist at the hospital's CCL. Sixteen relevant and feasible KPIs were selected for the CCL, inpatient department and the emergency department. The KPIs were structured hierarchically and clustered into categories. For user specific KPIs that address 'patient satisfaction,' proxies such as patient wait times and staff load schedules were used. Inter-departmental relations were accounted for based on the goals or executive KPIs for the hospital overall to ensure there were no undesired trade-offs where processes within the CCL interact with processes outside the CCL.

The KPIs were grouped into three categories: 'operational,' 'user related' and 'space related,' affecting the operational efficiencies, user experience and space utilization. The KPIs in each category were ranked and prioritized based on relative importance and impact on outcomes. This was also done for the other departments (inpatient and emergency departments) with the assigned priority weights shown in Table 2.

The process included: (1) identifying the relevant KPIs under the categories, (2) evaluating the KPIs from the simulation results, (3) normalizing the results against the benchmarks and goals set by the individual departments and the hospital, (4) arriving at an overall score for each CL.

Benchmarks are used for normalization, with the values based on the organizational goals, performance targets, experts' experience, evidence-based design, policies, etc. The results are normalized and given a score based on the assigned weights for the KPI.

The scores obtained for each category within the department helps understand tradeoffs between the categories. For example, between the operational and user related categories, ‘average patient wait times’, ‘staff load schedule’ which impact patient and staff satisfaction could have a higher priority to the ‘average LOS’, where LOS is the length of stay of the patient in the hospital (a critical KPI). In case of conflicts, the organization’s policies and preferences are obtained for the recommended action.

Similarly, the scores obtained between the departments help understand conflicting needs and consequences of actions on the KPIs. The simulation results and ranking based on the scores obtained within the department and between the departments is shown in Table 3.

Category	Key Performance Indicator (KPI)	Unit	Exec	CCL	IP	ED
Operations	Average LOS	days	20	-	10	-
	Bed turnover rate	#	10	-	25	25
	Cancelled Procedures	%	10	5	20	-
	Average LOS for ED	hours	10	-	-	10
	First case on-time starts	%	-	10	-	-
	Average procedural time for procedure	mins	-	5	-	-
	Turnaround time between cases (TAT)	mins	-	10	-	-
	Average time on pre & post procedure holding area by procedure	mins	-	5	-	-
	STEMI patients with D2B ≥ 90 minutes	#	-	15	-	-
	Average LOS post procedure	hours	-	5	-	-
	Overall Patient throughput	hours	-	5	-	-
User	Average Patient Wait Times	hours	15	15	25	25
	ED Waiting Time	mins	20	-	-	20
	Staff Load Schedule	hours	-	5	-	-
Space	Bed Occupancy	%	15	10	20	20
	Room / Asset utilization	%	-	10	-	-

High Priority Low Priority - Not Applicable

Table 2. Key Performance Indicators (KPI) and priority weights. Exec=Executive KPI; CCL=Cardiac Cath Lab KPI; IP=Inpatient Department KPI; ED=Emergency Department KPI; LOS=Length of stay.

	Exec		CCL		IP		ED		Score	Rank
CL2	75.6	3.8	84.2	58.9	65.9	6.6	97.3	14.6	83.9	3
CL3	98.3	4.9	97.0	67.9	98.3	9.8	97.3	14.6	97.2	1
CL4	91.2	4.6	98.6	69.0	92.6	9.3	91.8	13.8	96.6	2

Intra department and Inter department scores

Table 3. Simulation results and ranking. Intra=Within or inside the department; Inter=Between the departments.

5.3 Acting

Based on the comparative evaluations, the most desired—or least disruptive—action is communicated to the relevant stakeholders. This is done via the building’s two-way communication system, which as mentioned earlier in our case is by means of the VLC. Like other “recommender” systems, such as GPS-based driving instructions, the actors may accept or ignore the recommended action. Either way, their action will be sensed by the building, and become input for the next round of simulation/evacuation/action.

6. CONCLUSION AND DISCUSSION

We argue that total environmental adaptability—namely, buildings that can dynamically respond to and interact with their occupants—will be achieved when the building’s omniscience is harnessed in the service of its inhabitants. Such omniscience implies that the building, unlike its inhabitants, “knows” all that is happening within and around it at any given moment. When coupled with operational procedures and occupant profiles, such knowledge can be leveraged to predict and evaluate future events and recommend choosing the most beneficial one overall.

Towards this end, we presented a simulation-powered building management system that can sense human and building assets based on Visible Light Communication (VLC) technology; simulate alternative future building occupancy scenarios; evaluate them according to specific KPIs for the purpose of choosing one that will minimize/maximize users’ welfare and resource allocation.

We demonstrated such abilities in the case of a hospital’s Cardiac Catheterization Lab. Results indicate that it holds promise to enhance decision-making capabilities of building inhabitants, thus enabling building management strategies that support human needs and efficiency requirements, especially in mission-critical facilities.

The work reported here is on-going: the VLC system is being developed and tested in lab settings, with commitment for deployment at St. Bernardine Medical Center in California. Data is being gathered, through observations and interviews, of on-going CCL procedures, and event-based simulation software developed earlier is being adapted to whole-building scenarios.

ACKNOWLEDGMENTS

The research reported in this paper was made possible through grant #1838702 of the IIS Division of Information & Intelligent Systems, CSE Directorate for Computer & Information Science & Engineering, U.S. National Science Foundation, and grant #340753 of the European Research Council (ERC).

REFERENCES

1. Berger, H. Stephen, and H. Mark Gibson. Managing your hospital RF spectrum. *Biomedical instrumentation & technology* 47.3 (2013), 193-197.
2. Capolongo, S. *Architecture for flexibility in healthcare*, Franco Angeli, 2012.
3. Conti, J.P. What you see is what you send, *Engineering & Technology* 3.19 (2008), 66-68,

4. De Pourcq, K., Gemmel, P., and Trybou, J. Measuring Performance in Hospitals: The Development of an Operational Dashboard to Coordinate and Optimize Patient, Material and Information Flows. In H. Albach, H. Meffert, A. Pinkwart, R. Reichwald, & W. von Eiff (Eds.), Boundaryless Hospital: Rethink and Redefine Health Care Management, (2016), 159–181.
5. Kalay, Y.E. *Architecture's New media: principles, theories and methods of computer-aided design*. MIT Press, Cambridge, MA, 2004.
6. Kalay, Y. E. Evaluating and predicting design performance. Wiley, 2016.
7. Kim, J.K. and Schubert, E.F. Transcending the replacement paradigm of solid-state lighting. *Optics Express* 16, 26, (2008), 21835-21842.
8. Martel, T. J. Activation of the Cardiac Catheterization Lab for STEMI Patients. *Emergency Medicine* 49,6 (2017), 259–262.
9. Mozer, M.C. The Neural Network House: An Environment that Adapts to Its Inhabitants. *AAAI Spring Symp. On Intelligent Environments,* (1988), 110–114.
10. Pan, Z. Lang, T. Li, C. Di, M. Chen, G. Kalay, Y.E. Pai, R. and Wang, A. Visible Light Communication Cyber-Physical Systems-on- Chip for Smart Cities. *Journal of Communications*, 14, 12, 2019.
11. Rahimi, H., Kavosi, Z., Shojaei, P., and Kharazmi, E. (2016). Key performance indicators in hospital based on balanced scorecard model. *Journal of Health Management & Informatics* 4.1 (2017), 17-24.
12. Schaumann, D., Date, K., and Kalay, Y.E. An event modeling language (EML) to simulate use patterns in built environments." SimAUD, (2017), 21-28.
13. Schaumann, D., Pilosof, N.P., Sopher, H., Yahav, J., and Kalay, Y.E. Simulating multi-agent narratives for pre-occupancy evaluation of architectural designs." *Automation in Construction*, 106, 102896, (2019).
14. Shannon, R. E. Introduction to the art and science of simulation. Proceedings of the Winter Simulation Conference. (1998).
15. Martel T.J., Nambudiri V., Kirkman D., Martel J., Pappas L., and Jehle D. Activation of the Cardiac Catheterization Lab for STEMI Patients. *Emergency Medicine*. 2017 June; 49(6):259-262.