Summary for CIFE Seed Proposals for Academic Year 2019-20

Proposal number:	2019-11
Proposal title:	Building for the occupant: Optimizing building layouts for energy efficiency and organizational performance
Principal investigator(s)[1] and department(s):	Rishee Jain, CEE
Research staff:	Andrew Sonta
Total funds requested:	**$ 57,229**
Project URL for continuation proposals	**http://**
Project objectives addressed by proposal[2]	**Usable, Operable, Sustainable**
Expected time horizon	**2 to 5 years**
Type of innovation	**Incremental, Breakthrough**
Abstract (up to 150 words)	**The problem:** Managers of organizations and commercial offices are always seeking ways to improve worker performance and reduce energy consumption. Studies have demonstrated methods for improving each goal in isolation, but no research has focused on developing building designs that simultaneously address both. **The proposed solution:** We propose a data-driven socio-technical system for facility operations that can create designs and layouts that promote workplace collaboration and productivity while simultaneously reducing energy consumption in commercial buildings. **The proposed research approach:** We will deploy smart and connected plug load energy sensors within multiple organizations to develop our methods for occupant activity and network inference. We will also leverage novel data-driven spatial analysis and optimization techniques to evaluate and produce suggestions for new facility designs that will tightly couple occupant behavior, facility management, and organizational operations.

[1] The PI(s) must be academic council member(s) at Stanford.

1. ENGINEERING OR BUSINESS PROBLEM

Two of the most important indicators of a building's performance are its energy efficiency and ability to support the human activities for which it was designed. Researchers and practitioners have made vast progress in understanding each of these indicators in isolation, but few data-driven frameworks have been able to address the inextricable socio-technical link between them.

Imagine you are a manager of an organization in the knowledge industry. Chief among your goals is promoting collaboration among your employees—and thereby, hopefully, the innovative capacity of your organization. Your organization also cares deeply about environmental impact, and as a result your building has energy-efficient controls of heating, cooling, and lighting systems. You are considering redesigning the layout of your office space. It would be best, you think, to leverage your advanced building systems to reduce energy consumption by way of your new layout. But you, like most organizations, value your people and their productivity far more than your building's energy consumption. In fact, for the University of California system—whose 2016/17 operating budget is public data—total employee salaries, wages, and benefits were roughly **74 times** more expensive than utility bills, underscoring the notion that organizations are rational if they prioritize the productivity of their workforce over energy efficiency. As a result, for you it is integral that you create a new layout that stimulates collaboration and innovation all while reducing energy usage. For an organization with $74M in personnel costs and $1M in energy costs, a mere 2% improvement in productivity and 10% reduction in energy usage would result in $1.5M+ in added economic value.

> We aim to develop a data-driven socio-technical system for facility operations that can create designs and layouts that promote workplace collaboration and productivity while simultaneously reducing energy consumption in commercial buildings (Figure 1).

[2] For this and the next points, delete the answers that don't apply to your proposal.

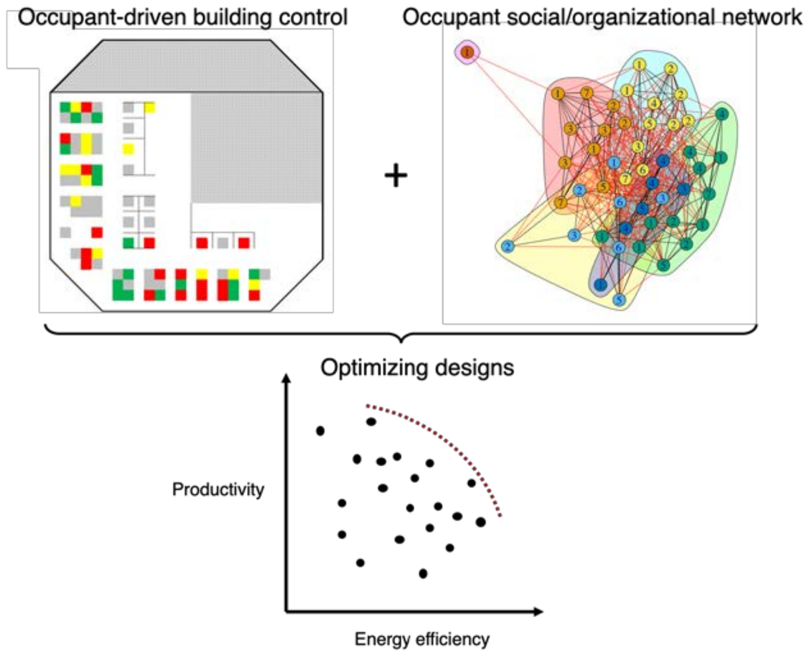

Figure 1: Theoretical optimization framework.

2. THEORETICAL AND PRACTICAL POINTS OF DEPARTURE

Part of the reason for our collective inability to co-optimize for both energy efficiency and building functionality is the lack of a reference point directly attributed to both. How can we measure the productivity impact of improving the insulation of a wall, or correctly sizing a window overhang? How does the addition of more meeting spaces—intended to improve collaboration—directly impact energy consumption? The traditional lenses for viewing each of our two goals are sufficiently different that it has been difficult to simultaneously consider both. It is only recently that the research around energy efficiency has found that the building occupant is the largest and most fundamental driver of building energy consumption (Hong and Lin 2012). This emergence of occupant-driven research opens new opportunities for more holistic building analysis. Our new reference point—the building occupant—brings energy efficiency into the realm of building function.

2.1. POD: Occupant-driven energy analysis

A key point of departure upon which our proposed work will build is the availability and analysis of data produced within buildings. In particular, IoT devices deployed at the level of the individual occupant create a wealth of information about users of facilities. Given that the occupant has been shown to be one of the largest drivers of the variability in energy consumption in buildings (Norford et al. 1994), researchers recently have developed data-driven methods and models for understanding occupant behavior (Zhao et al. 2014). Occupant behavior can be described broadly, from simple presence/absence data to occupant adaptive behaviors such as interacting with windows and thermostats (D'Oca et al. 2018). Presence/absence data can be used to derive more accurate occupant schedules, but as Feng et al. (2015) discuss, even this seemingly simple information can vary from the overall building occupancy level, to the occupancy status of a zone, to the individual location of occupants in the building. These kinds of occupant schedules can be valuable for creating more realistic energy simulations, aiding in the design of buildings.

As building systems that control heating, cooling, ventilation, and lighting become more advanced and controllable, contextual information about occupant activities can also be instrumental in improving the operation of buildings. Recent research has demonstrated the potential for *human-in-the-loop* control of many cyber-physical systems, including HVAC and lighting (D'Oca et al. 2018). By providing these advanced systems with richer information about the occupants' space utilization across the building, we can ensure they only provide HVAC and lighting systems where they are needed and when they are needed in the building (Dobbs and Hencey 2014).

2.2. POD: Spatial effects on occupant performance

Within commercial buildings, occupant-driven research has also recently focused on the performance of occupants in organizations. The study of productivity in organizations is many-faceted, but recent research has noted that space and design can have a large impact on organizational success. Even in the age of digital communication, classic studies have found that spatial proximity is a large predictor of the frequency of communication (Waber et al. 2014). Furthermore, researchers have found that by analyzing the paths in an academic office building, the more likely occupants are to have their paths overlap, the more likely they are to collaborate and be successful in those collaborations (Kabo et al. 2015, 2014).

An area of research at the intersection of organizational behavior and building design has defined a set of tools called *space syntax* (Bafna 2003). These tools enable building or urban layouts to be defined by the physical barriers and statistically analyzed with regard to connections between spaces. Researchers have found that offices with higher levels of *integration* and *connectivity*—space syntax measures related to the ease at which occupants can access other spaces than their own—lead to higher levels of communication and productivity (Congdon et al. 2007). Throughout this area of research, it is common to utilize the network of organizational and social relationships in an organization as input to analysis. Most often, researchers utilize questionnaires or extensive surveys in order to gather this network information, which are both time-intensive and expensive. Research has suggested that automatic inference of such networks could aid our ability to analyze existing organizational layouts and ultimately design more effective ones (Kabo 2018; Sailer and McCulloh 2012).

Ultimately, the research around occupant-driven energy efficiency and organizational success suggests that successful attempts to design and retrofit office spaces should consider both points of view. Recent work suggests that occupant-driven optimization of layouts has the potential to affect energy-efficiency (Yang et al. 2016), but we are aware of no work that seeks to co-optimize these layouts for both energy efficiency and occupant performance. Our dual approach will be crucial to driving change in buildings, as people drive the success of organizations far more than utilities. For an organization where people cost 74 times more than utilities, rational decision-making would prioritize the productivity of the workforce over energy efficiency. While occupant-focused energy interventions have shown potential, managers would be unlikely to make changes if they worry about disruptions to productivity. Our proposed work seeks to embed these organizational constraints—along with energy goals—into the process of redesigning workspaces.

3. RESEARCH METHODS AND WORK PLAN

Building upon our two key points of departure through the lens of the occupant—data-driven energy efficiency and organizational performance—we propose to develop a data-driven socio-technical framework for *optimizing commercial office layouts for energy efficiency and productivity*. Three steps summarize our proposed approach: (1) inferring occupant activities, (2) inferring social and organizational relationships among occupants, and (3) leveraging space-utilization information and the occupant network to optimize layouts. If successful, our proposed work will enable tight coupling of building systems with occupant activities, thus improving energy efficiency. Moreover, it will promote key aspects of productivity in organization (e.g., communication and collaboration), ensuring that organizational managers will be more open to spatial changes within the building.

3.1. Inferring occupant activities

Drawing upon our previous work (Sonta et al. 2018), we propose to continue developing methods for accurately inferring activities of occupants across building spaces using embedded sensor devices. As Figure 2 suggests, the raw data from IoT devices—in this case plug load sensor data—do not in themselves provide useful information about the building. We require methods that draw upon the specific engineering context to glean useful information from these data. Our work will build upon a set of statistical clustering tools based on variational Bayesian inference to translate raw plug load sensor data into information about the states of occupant activities. This work is inspired by research in the bioinformatics field that used similar tools to analyze human biological states based on times series heart-rate data (Costa et al. 2012). Similar to their work, our time-series data can be attributed to the different states of working within an office. The results from this analysis will provide us with highly granular and contextual information about the time and location of occupant activities in a building—the foundation upon which the following proposed work will build.

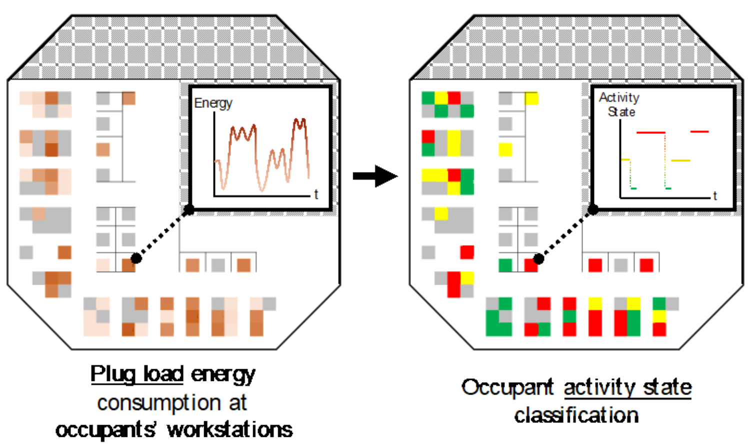

Figure 2: Inferring occupant activity states from plug load sensor data.

3.2. Inferring occupant social/organizational networks

The structure of organizations and the relationships among the people within them are important characteristics of organizational success. Typical organizational charts describe relationships according to team and hierarchical structure, but it is well known in the organizational behavior literature that the true structure of organizations is much more complex, subtle, and difficult to measure accurately. We theorize that various aspects of occupant dynamics influence how two occupants are related to one another, including spatial configuration of the building, the organizational structure of the group in the building, and the social relationships/friendships among the occupants. Given time-series information—inferred from plug load data (section 3.1)—about entities that are theorized to have relationships, various models can be utilized to infer the network structure of the entities. In the occupant network, the occupants themselves are the nodes, and the relationships among them are represented in the edge weightings (Figure 2). The *influence model* (Pan et al. 2012) and the *graphical lasso* (Friedman et al. 2008) are two models that have been shown to be effective in modeling relationships among entities given time-series data. We propose to investigate the effectiveness of these models in capturing true organizational structures within a building. We also propose to develop methods that make use of our engineering knowledge on building occupant dynamics to infer these ties among occupants. For example, we theorize that opportunity for social interaction comes about when occupants are expected to be in the building, but not working at their individual desks. This middle-ground state is likely captured by the *medium energy activity state* (yellow activity state in Figures 2 and 3). The more often two occupants share this medium state over time, the more likely they are to interact in person.

Once we infer these network relationships among occupants, we will benchmark the inferred network by capturing ground truth relationship information collected through surveys. Comparing two networks—such as the inferred and ground truth networks—is an active area of research in the domain of network science, but we plan to explore node-embedding techniques as well as network-level measures (e.g., community detection) to explore the ability of our network inference methods to capture true relationships among occupants.

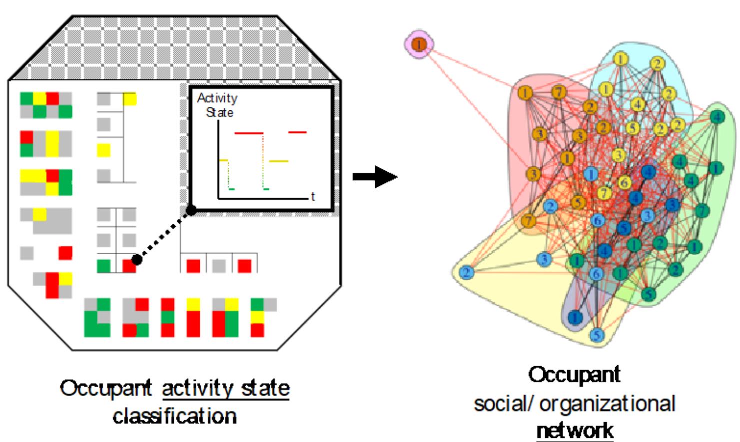

Figure 3: Inferring network structure from activity data.

3.3. Optimizing layouts for energy and organizational goals

Methods for understanding building occupant activities (section 3.1) and network structure within buildings (section 3.2) both have inherent value. Learning activities and the corresponding space utilization patterns can enable facilities to more closely match the operation of their systems with the dynamics of occupants. Learning network structure can help organizational managers understand the true ways in which their organizations function. We believe that in addition to these natural upshots, these methods will additionally enable the creation of tools for optimizing the layouts of buildings for our goals of energy efficiency and occupant performance.

As discussed in section 2.2, the design of office layouts can have significant impacts on collaboration and productivity. As a result, we can think about suggesting new layouts to promote such outcomes. Having learned the structure of the occupant network, we can attempt to strategically place occupants across the floorplan with strong organizational or social ties in order to promote communication and collaboration. Utilizing the language of space syntax, we can distill layouts into individual spaces and the connections among them. By mapping our learned network onto the space syntax network, we can evaluate how well we promote collaboration.

Any change in the layout of occupants is likely to have significant impacts on the energy performance of the building, as discussed in section 2.1. Having developed a method for understanding the activities of individual occupants, we can also evaluate how much different layouts are expected to affect the energy consumption of the building. Beyond evaluating the energy impacts of layout suggestions, we can also *optimize* layouts for energy-efficiency by clustering occupants with similar schedules. If we can colocate individuals who tend to arrive at the office around the same time, for example, we can leverage the controllability of shared HVAC and lighting services to delay operation until that group's typical start time. In preliminary analysis, we have found that a simple hierarchical clustering approach based on the Euclidean distance between occupants' time-series data vectors can produce groups of occupants with similarities in their activities. In Figure 4, we show a dendrogram of this clustering approach on a small office in Berkeley, CA. We see three relatively strong clusters as well as three relative outliers. In this preliminary proof-of-concept work, by grouping the strong clusters into the same zones within the building and simulating the energy performance of the building using *EnergyPlus* and *OpenStudio* software tools, we find that this simple clustering approach can save up to 3.3% in total annual energy consumption.

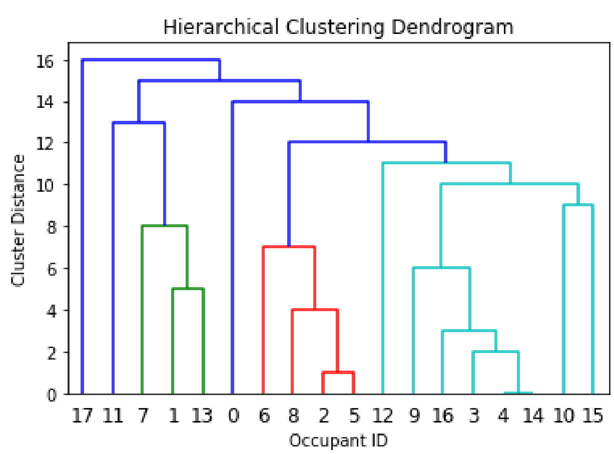

Figure 4: Grouping occupants with hierarchical clustering.

In this research, we aim to refine our methods for optimizing layouts for energy efficiency and combine them with methods that leverage space syntax and network structure to *co-optimize* for both energy efficiency and occupant performance.

4. EXPECTED RESULTS: FINDINGS, CONTRIBUTIONS, AND IMPACT ON PRACTICE

The overarching outcome of this work is the development of a data-driven socio-technical system for facility operations that can create designs and layouts that promote workplace collaboration and productivity while simultaneously reducing energy consumption in commercial buildings. This framework will serve as a toolset for commercial building management optimization and re-design. Using simple smart plug load sensor devices—or other similar IoT sensors—a facility manager will be able to conduct a "socio-space audit" of their building to understand how their spaces are being used and their organization is functioning in near real-time. Then, a facility manager will be able to utilize our system to explore and implement a set of optimized layouts designed to reduce energy use and encourage collaboration. From a theoretical perspective, we expect our contributions to center around new *methodologies* for inferring spatio-social networks in the built environment from sensor data as well as for optimizing commercial building layouts for energy and organizational goals. In the end, this work aims to enable facility managers to simultaneously fine-tune the performance of their buildings and their most important stakeholders—the occupants in their facilities.

5. INDUSTRY INVOLVEMENT

While no specific CIFE members were involved in the development of this proposal, we believe there are significant opportunities to leverage CIFE member companies for providing data and testing of our proposed data-driven socio-technical optimization framework for facility operations. In particular, CIFE member companies who develop design software (e.g., Autodesk) would be beneficial partners for understanding how our proposed methods would integrate with existing modeling and facility design software. Additionally, CIFE member companies who are design-construction-operators (e.g., Ryan Companies) and owner-operators (e.g., Gilead, Google, GSA) of commercial building facilities would be strong partners for further data collection and testing of our proposed framework.

6. RESEARCH MILESTONES AND RISKS

The timeline and milestones below follow from the research objectives described above and our current research activities in related areas:

1. Begin collecting plug load energy consumption data at Stanford Redwood City offices (and additional CIFE member company facilities if available) (***July 2019***).
2. Develop methodology for energy-focused building layout optimization and submit paper to the International Conference on Applied Energy (***August 2019***).
3. Further develop methodology for occupant network inference and submit paper to peer-reviewed academic journal such as *Environment & Behavior* (***September 2019***).
4. Design overall co-optimization framework using data from Stanford Redwood City (and additional CIFE member company facilities if available) building and submit paper to peer reviewed academic journal such as *Applied Energy* (***June 2020***).

Risks: One of the key risks in our proposed research plan is that it can be difficult to measure true energy outcomes and organizational outcomes after suggesting changes to facility layouts. We can mitigate the energy risk by leveraging the latest tools in building energy simulation, especially as recent advancements have focused on *occupant-driven* simulation. Once we develop the optimization framework, we can suggest to our test-bed site(s) (Stanford Redwood City, CIFE member company facilities if available) a range of new layouts that we believe accomplish our optimization goals. If the site chooses to make changes in accordance with our suggestions, we can conduct interviews with the managers of the space to glean insights into the impacts on perceived collaboration and productivity.

7. NEXT STEPS

We aim to utilize the initial results from this seed funding proposal as a mechanism to garner further interest from the Building Technologies Office (BTO) at the U.S. Department of Energy and industrial research partners. Several funding opportunities from BTO have been well-aligned with this research (e.g., BENEFIT) and we aim to leverage the proof-of-concept developed using this proposal in a full proposal for continued funding of 3-4 years. Additionally, we also believe that the initial results will demonstrate the potential benefits for an industrial partner who could provide both additional data and funding for continuing this work.

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