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# Critical Opportunity Areas for Building Performance

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# Critical Opportunity Areas for Building Performance Improvement

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## ABSTRACT

Green buildings are a proposed holistic solution to reduce energy consumption while simultaneously improving an array of factors affecting the indoor quality of life for building occupants. However, green building performance varies and may not achieve intended design goals. Research has concluded that no single factor determines the actual energy performance of buildings. To deliver energy-efficient buildings an integrated design that considers climate, technology, operation and maintenance and occupant behavior should be implemented. This work aimed to employ a holistic lens to relate human-building interaction and building performance characteristics. Specifically, systems theory and complex-problem solving techniques were employed to capture the dynamic interactions between the social and technical parts and processes of building systems and identify gaps causing the underperformance of buildings. Synergies not captured in the current design process but impact the ability of a building system to achieve its design goals were outlined. Performance metrics that a single system inadvertently affects along social, physical and economic dimensions were identified as well as high-impact opportunity areas for the creation of high-performance buildings. Addressing these synergies in the building equipment and full building design will enable stakeholder-centered systems integration, improving the efficiency and efficacy of buildings.

## 1. INTRODUCTION

Globally, the buildings' sector is the largest energy-consuming sector, accounting for over one-third of all final energy consumption, half of electricity use, and nearly one-third of total direct and indirect energy-related carbon dioxide emissions (IEA, 2013). In the U.S, the buildings sector is responsible for 40% of energy end-use (U.S. EIA, 2018). For this reason, there are significant research, policy, and practical efforts to improve the energy-efficiency and reduce the energy-related carbon emissions of the buildings sector.

In the U.S., sustainable buildings (e.g. Leadership in Energy and Environment Design (LEED) buildings and high-performance buildings (HPBs)) are the response to this grand challenge. These building philosophies recognize that energy consumption is connected to outcomes. "*Green buildings represent a holistic concept created in an effort to amplify the positive and mitigate the negative effects that the built environment can have on the natural environment, and on the people, who inhabit buildings every day the entire life cycle of a building"* (Kriss, 2014). The U.S Green Building Design Council established the green building rating tool LEED to transform how buildings are designed, constructed and operated. According to the LEED website, its purpose is to provide a framework that creates healthy, highly efficient and cost-saving green buildings for all building and community types. Similarly, HPBs are designed to have the potential to improve health, comfort, and productivity of the occupants with reduced energy consumption (National Institute of Building Sciences, 2008).

These outcomes are connected to design decisions. There is high potential for influencing the full life-cycle of building performance in the early design stages and this decreases dramatically overtime (Kohler & Moffatt, 2003). Therefore, building designers and developers are accountable for balancing these outcomes with the required criteria, available technology, and the collective experience of the industry to date. As system designers, the choices made in the early design stages often influence, and impose key constraints shaping downstream decisions (Proctor, & Van Zandt, 2008, p. 291). This means that downstream building owners and occupants are the receivers of these outcomes for the duration of their time with the building and, through building-related illness, possibly after. Relatedly, the National Institute of Building Sciences report to the U.S. Congress and U.S. Department of Energy on HPBs indicated that buildings must be designed and built in the context of larger human, environmental, and economic concerns; that all parts of the building need to be addressed in a cohesive, "whole building" approach (National Institute of Building Sciences, 2008). As Li & Hong (2014) concluded, no single factor determines the actual energy performance of high-performance buildings. They also concluded that to deliver energy-efficient buildings, an integrated design that accounts for climate, technology, operation and maintenance, and occupant behavior should be implemented. As such, sustainable building design often employs systems thinking in an attempt to optimize building outcomes. Nonetheless, green buildings often do not outperform their conventional counterparts in terms of energy-efficiency (Scofield, 2009) and/ (Oates, Dixon, Sullivan, & Kenneth 2012) or indoor environmental quality (Khoshbakht, Gou, Lu, Xie, & Zhang, 2018).

Missed building performance goals may be due to elusive or seemingly opposing design objectives (National Institute of Building Sciences, 2008). From an energy perspective, the building is a complex system in which the interaction of technologies almost always has an influence on energy demand (IEA, 2013). Given the system's complexity and significant uncertainty, it is difficult to predict the system (and subsystem) behavior and quantitatively analyze the tangible and intangible benefits during subsystem design and selection. The purpose of the work described herein is to provide a system-level perspective to disaggregate the phenomena that could be disabling system and subsystem performance.

## 2. FRAMING THE BUILDING AS A COMPLEX SYSTEM

The building is an open, complex system. Open systems are considered complex systems when they achieve the same final state from different initial conditions in different ways, interact with other systems in their environment, and their parts are under continuous exchange of matter with the environment (von Bertalanffy, 1968). These characteristics as well as the building's ability to adapt to those changes qualify it as a complex system. The mismatched system performance from the design phase speaks to the emergent, self-organizing and adaptive behavior inherent to a complex system. Definitions of these characteristics are in Table 1.

**Table 1:** Principles of Complex Systems

| **Principle** | **Description** | **Building-Specific Examples** |
|---|---|---|
| Holism/emergence | "*The behaviors and characteristics of the whole of a complex system emerge from the interaction of its parts, and the interaction between it and the environment dynamically. Therefore, the properties of the system cannot be determined or explained by its components alone"* (Xiong, 2011, p. 87) | The unpredictability of building energy consumption |
| Self-organization | *"The resulting organization's form is internal to the system and results from the interactions between the components, while being independent of the physical nature of those components. The organization can evolve either in time or space, can maintain a stable form or can show transient phenomena"* (Xiong, 2011, p. 83). | • An example of the first statement, the indoor air temperature and relative humidity does not have the same the physical distribution as might be expected from the form of the HVAC unit.<br>• An example of the second statement is fluidity of the indoor environmental quality. |
| Self-adaptation | This concept suggests that systems involve "*many components (agents) that adapt or learn as they interact"* (Xiong, 2011, p. 84). These | Building agents continuously adapt to changes in the environment and within the system. An example is the |

| | | |
|---|---|---|
| | systems are able to "*adapt to internal and external threats or changes through their own methods of self-communication or feedback*" (Castellini & Hafferty, 2008, p. 124). | continuous mass and energy exchange into, out of, and throughout the building. |

## 3. ANALYZING THE SYSTEM

To examine building systems as a complex system, this work applied three of the five general system rules noted by Ackoff (1999).

The nature of systems was summarized as the following (Ackoff, 1999, p.12-15):

1. "*System has one or more defining properties or functions.*
2. *Each part in the set can affect the behavior or properties of the whole.*
3. *The way that each essential part of a system affects its behavior or properties depends on (the behavior or properties of) at least one other essential part of the system.*
4. *There is a subset of parts that is sufficient in one or more environments for carrying out the defining function of the whole; each of these parts is necessary but insufficient for carrying out this defining function.*
5. *The effect of any subset of essential parts on the system depends on the behavior of at least one other such subset.*"

For the scope of this publication, rules 1 through 3 were assessed with a single example. For rule 1, it is assumed that the primary goal of sustainable buildings is to provide a healthy, resource-efficient built environment (US EPA, 2016). The objectives to reach that goal, stated in the Whole Building Design Guide, are listed below. Therefore, per system rule 2, the building subsystems play a role in the building achieving the design objectives. The productivity metric incorporates several facets of human factors not conventionally measured simultaneously, therefore, it has been segmented into health, comfort, and indoor environmental quality. Then per system rule 3, the subsystem interactions are assumed to enable building performance. However, for a complex system, complexity arises from these simple rule-based outputs. The emergent behavior of a complex system was illustrated while addressing rule 3. To briefly acknowledge rule 4, the environment of the system encompasses the uncontrollable factors that affect the system properties and performance of the system. The system can influence but not control transactional parts of the environment. The system has no influence or control over contextual parts of the environment (Ackoff, 1999). Occupant activity is a transactional environmental part of the building ecosystem. The outdoor environment, the outdoor environment's impact on the building envelope, the outdoor air conditions, the building envelope characteristics, and the building envelope configuration are contextual environmental parts of the building ecosystem.

The Whole Building Design Guide design objectives (WBDG, 2018):

1. *"Cost-effective: Pertains to selecting building elements on the basis of life-cycle costs (weighing options during concepts, design development, and value engineering) as well as basic cost estimating and budget control.*
2. *Safety and Security: Pertains to the physical protection of occupants and assets from man-made and natural hazards.*
3. *Sustainability: Pertains to environmental performance of building elements and strategies.*
4. *Accessibility: Pertains to building elements, heights and clearances implemented to address the specific needs of disabled people.*
5. *Functionality: Pertains to functional programming—spatial needs and requirements, system performance as well as durability and efficient maintenance of building elements.*
6. *Productivity: Pertains to occupants' well-being—physical and psychological comfort—including building elements such as air distribution, lighting, workspaces, systems, and technology.*
7. *Historic Preservation: Pertains to specific actions within a historic district or affecting a historic building whereby building elements and strategies are classifiable into one of the four approaches: preservation, rehabilitation, restoration, or reconstruction.*
8. *Aesthetics: Pertains to the physical appearance and image of building elements and spaces as well as the integrated design process."*

To assess the effects of the agents (building subsystems) on the system performance, the building subsystems were classified by their role in helping the system achieve its designed function. The subsystems were classified using the jobs-to-be-done model (JTBD) (Anthony, Johnson, Sinfield, & Altman, 2008) which transformed their classification from what they do to why they are important to the system. This framework is often employed in business contexts for customer-centered innovation. In this research, it was applied to frame a view of building systems as services designed to meet stakeholder needs.

**Table 2**: Generalized building parts from the jobs-to-be-done framework

| **Agent-based classifications** (inspired from a "jobs" perspective) | **Definition** |
|---|---|
| Controllable heating/cooling system | System that allows humidity and temperature control of the space |
| Contaminant removal system | System that removes pollutants from remaining indoors |
| Controllable lighting system | System that provides light indoors |
| Internal hazard system | Active method of protection against fire |
| Structural system | Building envelope assembly, foundation |
| System of ingress and egress | Path available for a person to leave a building, structure, or space (U.S. Access Board). |
| Water system | System that distributes and collects water |
| Energy sources | Primary energy source for part operation |
| Acoustical optimization system | Noise minimization solution |
| Occupancy | Thermal mass that releases energy and contaminants indoors with the ability to control other building systems |
| Communication Networks | Communications network that allows building systems to share information |
| Cooking Appliances | Devices that contain or manipulate a mass using thermal energy for meal preparation |
| Water and energy appliances | Devices that contain or manipulate a mass using water and energy to human needs |
| Energy only appliances | Devices that contain or manipulate a mass using energy to human needs |
| Electronics | Devices that operate using many small electrical parts (Merriam-Webster) |
| Context-specific energy consuming equipment | Devices that consume energy for business contexts |
| Furnishings and finishings | Objects intended to make a space suitable for living or working |
| Space Layout | Look and feel of a space, spatial configuration, location, amenities, floor plan |
| Exterior attachments | Building attachments (e.g., external shading devices) |

To address rule 3, a square matrix highlighting pairwise linkages between every agent and every other agent was used to systematically research the subsystem to subsystem interactions. An example matrix is shown in Figure 1. During that investigation, the connections with other agents and their relevance to system performance were documented. The level of knowledge available for each agent-to-agent interaction was assessed. The research highlighted the connection between systems, each system's impact on people, and related performance gaps. For the scope of this paper, the heating and cooling subsystem was reviewed, as shown in Figure 2. High-impact opportunity areas lie in the interactions that have been explicitly investigated but not empirically related, and in those where a relationship has been indicated but has not been explicitly investigated. There may also be opportunity areas in relationships that have been empirically related, as some important system-level variables may be neglected in these relational equations. Potentially high-impact opportunity areas include relationships that have not been explicitly investigated.

| | **Agent 1** | **Agent 2** | **Agent 3** | **Agent 4** | **Agent 5** | **Agent 6** | **Agent 7** | **Agent 8** | **Agent 9** | **Agent 10** |
|---|---|---|---|---|---|---|---|---|---|---|
| **Agent 1** | | | | | | | | | | |
| **Agent 2** | | | | | | | | | | |
| **Agent 3** | | | | | | | | | | |
| **Agent 4** | | | | | | | | | | |
| **Agent 5** | | | | | | | | | | |
| **Agent 6** | | | | | | | | | | |
| **Agent 7** | | | | | | | | | | |
| **Agent 8** | | | | | | | | | | |
| **Agent 9** | | | | | | | | | | |
| **Agent 10** | | | | | | | | | | |

**Figure 1**: Example square matrix used to analysis agent to agent relationships

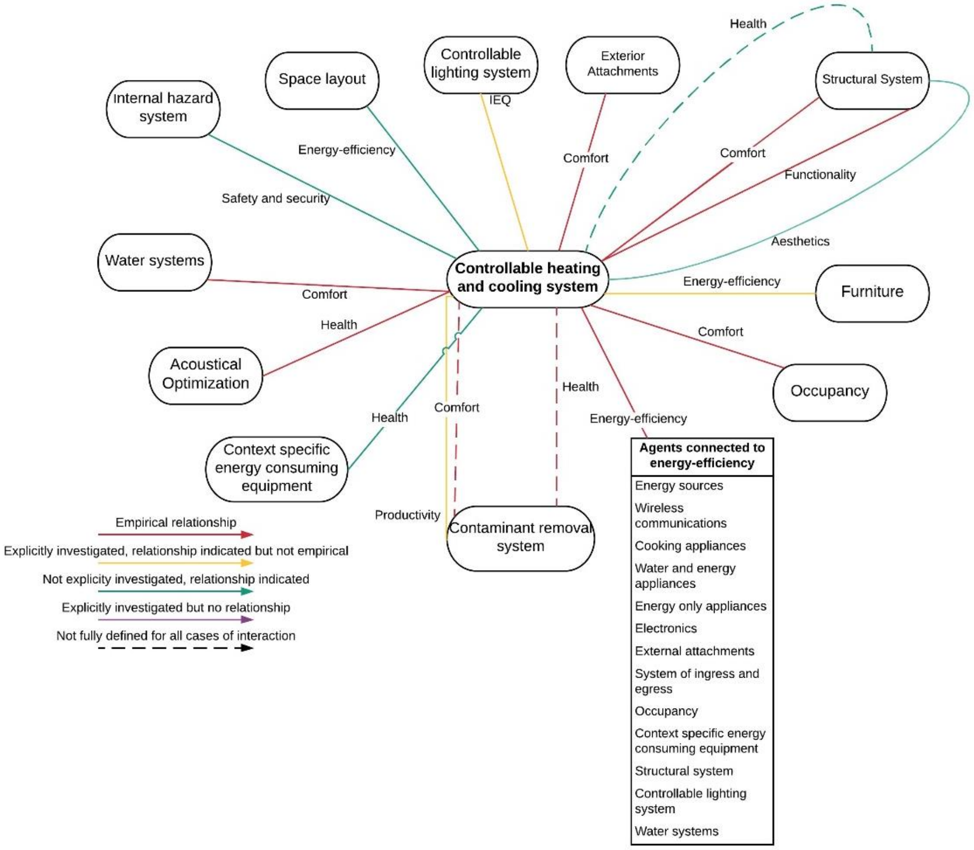

**Figure 2**: System-level view of the thermal control system

## 4. COUNTER-INTUITIVE IMPACTS ON SYSTEM PERFORMANCE

The emergent behavior of the building is highlighted by the counterintuitive synergies between agents as shown in Figure 2 and further explained in the proceeding discussion. These system synergies have influence on agent-related design goals, and often impact the occupant, revealing opportunities for improved equipment, and building subsystem design. The design goal for the space conditioning system is to provide a system that maintains a **comfortable** and

**healthy** internal environment for the building occupants (Mitchell & Braun, 2013). Since space conditioning is the most significant energy consumer in U.S. buildings (Berry, 2013) (Michaels, 2016), it is important to balance space conditioning needs with **energy-efficiency**. The controllable heating and cooling system connection to other building parts is shown in Figure 2. Failure to design the equipment and building subsystems without absorbing their interdependence with other systems in the building context drives performance gaps today and provides opportunities for future improvement to design processes, as outlined below.

There are synergies with other building parts that influence the thermal control system's ability to achieve its intended design goals of thermal comfort and energy efficiency, as described in ASHRAE Standard 55 which outlines means to estimate occupant **thermal comfort** (Eddy, Alspach, Arens, Aynsley, Bean, Hartman, & Humble, 2017). Ideally, it's employed to ensure that 80% of the building occupants are thermally satisfied. However, this Standard neglects the impact of a counter-intuitive synergy between thermal comfort and the exterior attachments. As reported in one study, "*Shading systems significantly improved the operative temperature and radiant temperature asymmetry during cold sunny days".* (Bessoudo, Tzempelikos, Athienitis, & Zmeureanu. 2010, p. 1). Similarly, Tzempelikos, Bessoudo, Athienitis, & Zmeureanu (2010) determined that irrespective of the glazing type, shading enhanced thermal comfort conditions by reducing extremes in operative temperature and radiant temperature asymmetry. Beyond shading, the use of water systems and cooking can influence occupant thermal comfort. They are moisture sources (Hens, 2012); and moist air is perceived as uncomfortable due to its potential to facilitate latent heat loss. Low relative humidity can induce electric charges when in contact with an insulator, creating further occupant discomfort. Relative humidity also affects human's perception of fresh air. Dryer, cooler air is perceived as fresher than warm and humid air, highlighting an important link between thermal control, moisture, and IEQ. Lastly, the although thermal impacts from solar radiation and artificial lighting are quantitatively captured from an energy perspective, the intangible effects of lighting on **IEQ** represent another system-to-system synergy that is not quantitatively evaluated.

Regarding **energy-efficiency**, the thermal load on a HVAC system is calculated using the heat balance method (ASHRAE, 2013). This method considers the effect of outdoor weather, internal heat sources and indoor set-points on the thermal load. However, the uncertainties associated with these factors are neglected in design which can cause significant variance in the peak cooling load (Gang, Wang, Shan, & Gao, 2015). This oversight would result in an oversized system. An oversized system yields higher initial costs, lowers the system energy-efficiency, increases utility costs, and possibly reduces thermal comfort. The conventional heat balance method also neglects the counter-intuitive thermal load relationship with the *space layout* and *furniture*. Raftery, Lee, Webster, Hoyt, & Bauman (2014) studied the impact that furniture and contents (i.e. internal mass) have on zone peak cooling loads using a perimeter zone model in EnergyPlus with the zone parameters of the HVAC system type (overhead, underfloor, and thermally activated building system (TABS)), orientation, window to wall ratio, and building envelope mass. The internal mass parameters were the amount, area, and the material type. Their results highlighted that adding internal mass changed the peak cooling load by a median value of −2.28% (−5.45%, −0.67% as the lower and upper quartiles respectively). The thickness of the internal mass surface meaningfully affected the peak cooling load where thinner surfaces increased the peak cooling loads. Raftery et al., (2014) also noted the low amount of accurate recommended values for internal mass models available. The authors suggested that the quantity, distribution, and the average thickness in aggregate, and material type of furnishings be explored in future buildings research. Although, the thermal gains through the building envelope are considered in the heat balance method, this method does not fully capture the synergy between the heating and cooling system and the building envelope. It is known that from an energy perspective, free sunlight, thermal mass, insulation, shading, reflective surfaces and natural ventilation can be used to reduce cooling loads in the summer (IEA, 2013); however, optimizing this synergy is not common practice. Seasonal optimization of the heat flow from solar radiation is a challenge and the technology are costly (IEA, 2013). Moreover, these synergies are captured in the development stages only if early decision makers pursue the benefit of spending additional time in advanced building envelope design. These findings show the opportunities present to reduce the cost or technical barriers to building envelope and thermal control system synergy realization, so early decision makers are influenced to and can easily capture them.

Thermal comfort is also connected to energy-efficiency. For example, Shahzad, Brennan, Theodossopoulos, Hughes, & Calautit (2017) examined office layouts with high and low levels of thermal control. Their analysis indicated that a balance between thermal comfort, energy efficiency, space layout and occupant control is required, and user satisfaction, user comfort, and energy consumption were considerably higher in the traditional cellular office with a high level of control compared to the low-level control contemporary open plan office.

The thermal control system also impacts other performance metrics not captured during the design process. The impact of the heating and cooling subsystem on occupant's **productivity** (in terms of human performance) are not primary design metrics. However, the delivered air volume at the desired temperature and humidity conditions has a relationship with sound. The air temperature, sound, and ventilation rate are an environmental synergy that can affect mental workload and cognitive fatigue. The combination of high intelligibility of irrelevant speech, high room temperature and low ventilation rate impairs the perceived working conditions and cognitive performance. It is possible to suggest that by designing room acoustic conditions, thermal conditions, and ventilation rate adequately, satisfaction with work environment is increased, somatic symptoms are decreased, and the possible impairments of work performance can be avoided. Based on subjective assessments, mental workload, cognitive fatigue and symptoms have been shown to be higher and environmental satisfaction was lower in environments with higher room temperatures (29°C), highly intelligible speech (low absorption and high sound masking level), and negligible fresh air supply rate (2 l/s per person). In fact, a change in temperature can have the same effect on productivity as a change in sound level. The neutral sound pressure of a typical air-conditioned office is between 45 dB and 70 dB. A 1°C temperature change has the same effect on productivity as a change in noise of 2.6 dB (Al Horr, Arif, Kaushik, Mazroei, Katafygiotou, & Elsarrag, 2016). A specified room noise criterion must often be demonstratively met within precise limits during building commissioning, procedures to demonstrate compliance vary in effectiveness due to significant point-to-point sound pressure level variation (ASHRAE, 2013). At the time of writing the 2013 ASHRAE Handbook, there was no general agreement in the industry on an acoustical measurement procedure for commissioning HVAC systems. AHRI Standard 885 incorporates a suggested procedure for field verification of NC/RC levels (ASHRAE, 2013).

The controllable heating and cooling systems also have inadvertent **health** impacts. Difficulty in <u>acoustical optimization</u> of HVAC systems can impact sleep quality (Öhrström & Skånberg, 2004) and increase stress levels at work (Al Horr et al. 2016) especially in aggregate with <u>context-specific energy-consuming equipment</u> such as fax machines and telephones. From a thermal perspective, heating systems that rely on wood or coal can lead to serious health effects such as respiratory and cardiovascular mortality and morbidity, as carcinogenic compounds are emitted (World Health Organization, 2015).

Improper management of the heat, moisture and air flow through the building envelope may impact the building **functionality**, **aesthetics**, and occupant **health**. For example:

> *"This may cause electrochemical corrosion of metal components, the chemical deterioration and dissolution of materials such as gypsum sheathing, ceiling tiles, especially wood products on the exterior wall, discoloration of building finishes, volume changes (swelling, warping and shrinkage) that can cause degradation of appearance, structural failure, cracking, etc., freeze-thaw deterioration of concrete, stone, and masonry, especially for buildings in cold areas if the building materials contain moisture, the increase of material thermal conductivity due to the moisture within the material, the growth of biological forms, including molds, mildews, mites, etc*." (Zhong, 2008, p. 1)

Building-level hygrothermal analysis and the impact on durability, thermal comfort, indoor air quality, energy-efficiency, and building-related respiratory issues, skin and eye irritation are quantified, and ideally, considered in the conventional design process. Nevertheless, building degradation may cause building envelope assembly to fail as a sound barrier for traffic noise which has its own set of health issues not considered in the conventional design process. Also, building aesthetics plays a role in design decisions, and these decisions tie to energy-efficiency. For example, highly reflective surface colors in hot climates especially on roofs would reflect more significantly more sunlight than a conventional color. "*An ordinary gray roof might reflect 20% of sunlight, a red roof 40% and a bright white roof 80%"* (IEA, 2013, p.118). However, the intangible benefit of aesthetics are not quantitatively evaluated with energy-efficiency.

Heating systems that are not appropriately designed can encourage building occupants to take supplementary measures that are ultimately unsafe. As a result, heating equipment accounted for 15% of the reported home fires in 2011-2015, 19% of home fire deaths, and $1.1B in direct property damage (Campbell, 2017) affecting the **safety and security** objective of the <u>internal hazard system</u>. Energy insecurity is another result of sub-optimized HVAC system design as 11% of households keep their home at an unhealthy or unsafe temperature, one in five households reduce or forgo necessities like food and medicine to pay an energy bill, and 14% of households receive an energy service disconnection notice (US EIA, 2017).

## 5. CONCLUSION

The controllable heating and control system is connected to more than indoor air quality related health concerns, thermal comfort and energy-efficiency. It is related to aesthetics, productivity, building safety, energy security and functionality. Similarly, the space layout, furniture, exterior building attachments, the climate, internal heat sources and indoor set-points have a larger influence on the subsystem achieving its design goals than is routinely quantitatively considered in design.

The building is a complex system and the building energy problem is a complex problem linked to outcomes. However, existing design methods and metrics do not fully capture the longitudinal impact of decisions or enable quantification of the complex synergies that emerge during operation. This work provided initial insight into understanding the system complexity, connecting subsystems to outcomes, and identifying opportunities to close performance gaps. With the proper methods, work of this nature has the potential to enable designers to quantify the tangible and intangible benefits of their decisions in the planning and construction phases, reducing downstream system performance gaps.

## 6. REFERENCES

1. About USGBC | USGBC. (n.d.). Retrieved from https://new.usgbc.org/about
2. Ackoff, R. L. (1999). *Re-creating the corporation : a design of organizations for the 21st century*. Retrieved from https://ebookcentral.proquest.com
3. Al Horr, Y., Arif, M., Kaushik, A., Mazroei, A., Katafygiotou, M., & Elsarrag, E. (2016). Occupant productivity and office indoor environment quality: A review of the literature. *Building and Environment*, *105*, 369–389. http://doi.org/10.1016/j.buildenv.2016.06.001
4. Anthony S.D., Johnson M.W., Sinfield J.V., Altman E.J. (2008). *The Innovator's Guide to Growth: Putting Disruptive Innovation To Work*. Boston, MA: Harvard Business Press.
5. ASHRAE. (2013). Nonresidential Cooling and Heating Load Calculations. *ASHRAE Handbook – Fundamentals*, 1–65. Retrieved from
6. Berry, C. (2013). *Table CE3.1 Household Site End-Use Consumption in the U.S., Totals and Averages, 2009*. Retrieved from https://www.eia.gov/consumption/residential/data/2009/c&e/ce3.1.xlsx
7. Bessoudo, M., Tzempelikos, A., Athienitis, A. K., & Zmeureanu, R. (2010). Indoor thermal environmental conditions near glazed facades with shading devices e Part I: Experiments and building thermal model. *Building and Environment*, *45*, 2506–2516. http://doi.org/10.1016/j.buildenv.2010.05.013
8. Campbell, R. (2017). Home Fires Involving Heating Equipment. Retrieved from https://www.nfpa.org/-/media/Files/News-and-Research/Fire-statistics/Major-Causes/osHeating.pdf
9. Castellani, B., & Hafferty, F. (2009). *Sociology and Complexity Science A New Field of Inquiry* (Understanding Complex Systems).
10. Eddy, J., Alspach, P. F., Arens, E. A., Aynsley, R. M., Bean, R., Hartman, T. B., Humble, J. (2017). Thermal Environmental Conditions for Human Occupancy, *2017*.
11. US EPA. (2016). Green Building |US EPA. Retrieved May 30, 2018, from https://archive.epa.gov/greenbuilding/web/html/
12. Gang, W., Wang, S., Shan, K., & Gao, D. (2015). Impacts of Cooling Load Calculation Uncertainties on the Design Optimization of Building Cooling Systems. Energy and Buildings, 94, 1-9. doi: 10.1016/j.enbuild.2015.02.032
13. Hens, H. (2012). Building physics heat, air and moisture: Fundamentals and engineering methods with examples and exercises (2nd ed.). Berlin, Germany: Ernst & Sohn.
14. How much energy is consumed in U.S. residential and commercial buildings? - FAQ - U.S. Energy Information Administration (EIA). (2018). Retrieved May 25, 2018, from https://www.eia.gov/tools/faqs/faq.php?id=86&t=1
15. IEA. (2013). *Transition to Sustainable Buildings*. *Iea.Org*. http://doi.org/10.1787/9789264202955-en
16. Khoshbakht, M., Gou, Z., Lu, Y., Xie, X., & Zhang, J. (2018). Are green buildings more satisfactory? A review of global evidence. *Habitat International*, (February). http://doi.org/10.1016/j.habitatint.2018.02.005
17. Kohler, N., & Moffatt, S. (2003). Life-cycle analysis of the built environment. *Industry and Environment*, *26*(2–3), 17–21. Retrieved from http://www.bvsde.paho.org/bvsaia/fulltext/lifecycle.pdf

18. Kriss, J. (2014). What is green building? | U.S. Green Building Council. Retrieved May 29, 2018, from https://www.usgbc.org/articles/what-green-building
19. LEED | USGBC. (n.d.). Retrieved May 21, 2018, from https://new.usgbc.org/leed
20. Li, C., & Hong, T. (2014). Revisit of Energy Use and Technologies of High Performance Buildings. ASHRAE Transactions, 120, 1GG.
21. Michaels, J. (2016). *Table E1. Major fuel consumption (Btu) by end use, 2012*. Retrieved from https://www.eia.gov/consumption/commercial/data/2012/c&e/pdf/e1.pdf
22. Mitchell, J. W., & Braun, J. E. (2013). *Principles of heating, ventilation, and air conditioning in buildings*. Hoboken, NJ: Wiley.
23. National Institute of Building Sciences. (2008). Assessment to the US Congress and U.S. Department of Energy on high performance buildings. Retrieved from https://c.ymcdn.com/sites/www.nibs.org/resource/resmgr/HPBC/NIBS_HighPerformanceBuilding.pdf
24. Oates, D., Sullivan, K. T., Ph, D., & Asce, M. (2012). Postoccupancy Energy Consumption Survey of Arizona ' s LEED New Construction Population, *138*(June), 742–750. http://doi.org/10.1061/(ASCE)CO.1943-7862.0000478.
25. Öhrström, & Skånberg. (2004). Sleep disturbances from road traffic and ventilation noise—laboratory and field experiments. Journal of Sound and Vibration, 271(1), 279-296.
26. Proctor, R., & Van Zandt, T. (2008). Human factors in simple and complex systems (2nd ed.). Boca Raton, Fla.: CRC Press.
27. Raftery, Lee, Webster, Hoyt, & Bauman. (2014). Effects of furniture and contents on peak cooling load. Energy & Buildings, 85, 445-457.
28. Scofield, J. H. (2009). Do LEED-certified buildings save energy? Not really. http://doi.org/10.1016/j.enbuild.2009.08.006
29. Tzempelikos, Bessoudo, Athienitis, & Zmeureanu. (2010). Indoor thermal environmental conditions near glazed facades with shading devices – Part II: Thermal comfort simulation and impact of glazing and shading properties. Building and Environment, 45(11), 2517-2525.
30. U.S. Energy Information Agency. (2017). RECS: One in three U.S. households faced challenges in paying energy bills in 2015. Retrieved May 25, 2018, from https://www.eia.gov/consumption/residential/reports/2015/energybills/
31. Varjo, Hongisto, Haapakangas, Maula, Koskela, & Hyönä. (2015). Simultaneous effects of irrelevant speech, temperature and ventilation rate on performance and satisfaction in open-plan offices. Journal of Environmental Psychology, 44, 16-33.
32. Von Bertalanffy, L. (1968). General System Theory. *Georg. Braziller New York*, *1*, 289. Retrieved from http://books.google.es/books?id=N6k2mILtPYIC
33. World Health Organization. (2015). Residential heating with wood and coal: health impacts and policy options in Europe and North America. WHO Regional Office for Europe. http://www.who.int/iris/handle/10665/153671
34. WBDG. (2018). Design Objectives | WBDG Whole Building Design Guide. Retrieved May 25, 2018, from https://www.wbdg.org/design-objectives
35. Xiong J. (2011) Foundation for Establishing NSE: Complexity Science. In: New Software Engineering Paradigm Based on Complexity Science. Springer, New York, NY
36. Zhong, Z., & Purdue University. School of Mechanical Engineering. (2008). Combined heat and moisture transport modeling for residential buildings.