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Computational Needs for Design, Optimization, Control, and Analysis of Energy Efficient Buildings

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Buildings are complex systems that span multiple time and spatial scales, contain many components whose behaviors are governed by a variety of physics rules, and exhibit complicated dynamics caused by stochastic occupant and energy usage patterns coupled with interactions among the building component systems. This complex system evolves over its life cycle, which typically spans decades or longer, and may be used for purposes never imagined during initial design. Moreover, buildings interact externally with each other, their environment, and utilities. The complexity of this system combined with the pressing need to reduce energy consumption for the entire societal inventory of buildings makes the need for advanced computational tools indisputable. Such tools could enable, for example:

- consideration of energy, water, air, and occupant flows much earlier (and often) in the design process (efficient, predictive, real-time simulations enable architects or engineers to see how their choices affect energy consumption over whole lifecycle);
- an iterative or co-design process, where the potential impact of decisions in each lifecycle phase (architecting, economics/fundraising, structural engineering, internal and functional engineering, construction, operations) can be assessed and reconsidered before physical construction begins; and
- design for evolving energy supply systems supporting buildings, including buildings that can adapt to energy costs or availability of renewable energy.

Current computational tools provide remarkable capabilities to aid in understanding and designing buildings and their energy-related systems. However, several advances will have transformational impact on the art and practice of building design and operations.

Risk quantification: Convincing consumers of the benefits of new technologies is critical to achieving zero energy buildings. The underlying technical challenge here is quantification of the risk. Currently, the wide and unpredictable gap between expected and observed performance hinders demand on efficient technologies. Narrowing this gap requires higher fidelity simulations and mathematically principled methods for predicting building performance, plus methods for quantifying the sensitivity of performance to discrepancies between as-designed and as-built or as-evolved. Quantifying the performance gap requires a model that can account for design through construction, uncertainty estimates for individual components, and uncertainty propagation techniques recognizing inter-component dependencies. Risk quantification techniques are now being applied to complex systems, and the field is ready to make an impact on building simulations.

Optimal design of new buildings: Optimal building design represents a significant and challenging departure from “classical” engineering design. First, while the function of a building is well established (provide shelter, control climate, support a finite number of human activities), that function places strikingly few constraints on the form of the resulting building. This leads to an innumerably large search space that significantly complicates the search for the “optimal” design, even after accounting for indirect constraints imposed by structural mechanics, building codes, and regulators. Second, the design process is not well-characterized

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by a single objective, and frequently several central objectives are qualitative (e.g., aesthetics, usability). This analysis approaches that can enumerate trade-offs among competing objectives, and can account for uncertainty or ambiguity in the relative optimality of qualitative objectives. Third, the multitude of competing design goals necessitates new advancements in multicriteria optimization, analysis, and decision support.

Design for building life cycle: Buildings are used for many different purposes during their lifetimes. The design process should take into account not only the variance in near-term usage but also potential long-term usage patterns along with associated retrofit operations. Despite the vast importance of taking the life cycle of a building into account, the enormity of the problem limits efforts in this era. Recent breakthroughs in computational optimization for solving stochastic mixed integer linear optimization problems with recourse provide a sound basis, but significant advances are needed to extend these capabilities to nonconvex nonlinear problems.

Model reduction and hierarchical models: Both risk quantification and optimizing building performance for full life cycles require running many simulations with slightly different parameters characterizing scenarios. Given the large number and high complexity of system components, full-scale high-fidelity simulations may be prohibitively expensive, even for state-of-the-art high performance computing platforms. Using lower fidelity models on the other hand will decrease confidence in results. A promising alternative is to build surrogate models in a principled way, and use a hierarchy of models to represent the overall system. Network models for buildings are particularly interesting in this regard. Recent methods in quantifiably accurate network models for biological and chemical systems should be applicable to buildings as well.

Modular software design: Many developing technologies will have impact on building energy efficiency and must be integrated into simulations. Such delivery requires a modular software framework that separates modeling and solver components. This will have crucial advantages such as:

a) modeling flexibility: building experts can focus on modeling, not solvers or algorithms;
b) opportunity to adopt and seamlessly transition to state-of-the-art solvers;
c) ability to effectively utilize hardware resources, independent of computing platform;
d) ability to assemble components of appropriate fidelity to best match the problem at hand, available computational budget, and analysis needs.

Such modular design, together with appropriate multi-fidelity, data-informed models, facilitates creation of software tools appealing to architects, engineers, and building operators who wish to perform "what-if?" studies and trade-off analyses, accounting for engineering principles and code constrains as well as aesthetic and functional concerns.

Quantifying "best possible" performance: A critical benchmark for the current operational performance of a system is its best attainable performance. Identifying realistic optimal performance will require robust capabilities for large-scale dynamic optimization of complex stochastic processes. This is further complicated by a general lack of understanding of a building's state *as-built*. Buildings typically have insufficient instrumentation to allow reliable regression of building state for even simple building models. Key parameters, such as activities of occupants, are not measured directly; and those measured are often grossly aggregated (energy use is metered for the building as a whole) or inferred from indirect measurement (current external environment conditions from metropolitan weather data). The effective over-parameterization of even simple models leads to significant uncertainty in the regressed state which must be propagated through models resulting in "best estimate plus uncertainty" in achievable performance.

Intelligent control and data assimilation: The importance of control systems for building energy efficiency has long been recognized. What is changing is the capability to collect large volumes of data, and assimilate and analyze this data in near real time to predict usage patterns, which can be used for more intelligent control systems. These must be distributed control systems, as the increasing complexity of operational systems makes centralized control extremely difficult. High fidelity models and design tools can also benefit from this wealth of data. Early Sandia studies demonstrated that a CONTAM model for building airflows, enhanced with real-time boundary condition information from building sensors, was significantly more accurate. Such calibrated tools can offer building operators insight into building conditions, even in sensor-less areas.

Energy portfolio management: While traditionally a primary goal for an energy efficient building is minimizing its overall net external energy demand, it is increasingly clear that buildings are a part of larger systems that must be coordinated to achieve maximal energy savings. For example, while installing photovoltaics to meet a significant portion of a building's electrical demand will reduce net draw from the electric grid, those gains are partially offset by the utility's need for increased spinning reserves to handle intermittent loads the building will place on the grid. Alternatively, coordinating HVAC utilities across several buildings (like households in a neighborhood) can reduce the overall variability in instantaneous grid load, and allow utilities to reduce spinning reserve levels. An even more revolutionary advance would be buildings and control systems designed to use energy primarily when it is available from renewable sources, helping achieve true zero-energy designs. This demands consideration of energy storage, scheduled consumption, and feedback as part of the overall building design process.

This large-scale problem presents modeling, planning, and operational challenges that are significantly beyond the scope and capabilities of current tools. Further, such tools must be applied in a staged approach over time with recourse accounting for data from distributed building sensor networks, net metering, financial pressure, and environment, to make optimal decisions given current and historical conditions.

Human factors modeling: To effectively predict the true energy savings derived from new technologies, their use context must be carefully considered. For example, a new lighting technology (such as LEDs) may promise significant energy savings over traditional incandescent or fluorescent systems. However, factors such as the spectral response of the human eye can significantly reduce the net benefit. Tools modeling radiation transport could assess visibility and comfort under various lighting scenarios. In addition, the way occupants adopt and elect to use building components can have a huge impact on cost savings. Developing meta-models for human factors in a way that can be integrated with high-fidelity simulation tools and optimization and uncertainty analyses could increase their impact on architectural engineering.